THE SOLAR SYSTEM
AND ITS ORIGIN

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by

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PREFACE

This little volume represents the lectures given at the University of Virginia on the Page-Barbour Foundation in 1934. They should be regarded as a general presentation of the present state of knowledge and theory, and not as a technical contribution to cosmogony. A somewhat informal style, with occasional use of the first personal pronoun, has therefore been deliberately retained.

Material has been gathered from many sources; acknowledgment is specially due to Professor T. C. Chamberlin's *The Two Solar Families* (University of Chicago Press), to Professor V. M. Goldschmidt's geochemical papers (mainly in the Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, 1931-33), and above all to Dr. Harold Jeffreys' *The Earth* (Cambridge, 1929).

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Princeton University Observatory
November 8, 1934

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I

THE DYNAMICAL PROPERTIES OF THE SYSTEM

THE unsolved problems of Nature have a distinctive fascination, though they still far outnumber those which have even approximately been resolved. It may therefore be permissible to discuss the present situation of one of these, even though the outcome should no more than justify the conventional resolution to "report progress" and turn to other matters.

Speculation on the origin of our solar system is centuries old—much older, indeed, than the recognition of those dynamical and physical laws upon which alone any rational hypothesis must be based, or than the knowledge of facts enough to serve as adequate tests of such theories. In a present-day survey of the field it is well to reverse the historic order, and consider first the known properties of the system, and then the theories which have been advanced to account for them, their successes and their limitations.

1. First among the characteristics of our system is its extreme *isolation*. Imagine a map, drawn accurately to scale, on which Pluto, at its remotest, is a foot from the Sun. The Earth's orbit would be half an inch across

and Jupiter an inch and a quarter from the Sun; but the nearest star would be a full mile away!

A generation ago, when few measures of stellar distances had been made, there was hope of finding nearer stars. But among the thousands of stars which have now been investigated for parallax one little one has been found, half as far away again, and two more not quite twice as distant as Alpha Centauri, which retains its primacy. Since special attention has been paid to those stars which give promise of being our near neighbors, it is now practically certain that if any nearer star exists, it must be exceedingly faint.

These studies have shown that interstellar distances are usually as great as this, so that the Sun is no lonelier than its neighbors; indeed, it is a very commonplace star,—dwarfish, though not minute,—like hundreds, nay thousands, of others. By accident the brighter component of Alpha Centauri (which is double) is almost the Sun's twin in brightness, mass, and size. Could this Earth be transported to its vicinity by some supernatural power, and set revolving about it, at a little less than a hundred million miles' distance, the star would heat and light the world just as the Sun does, and life and civilization might go on with no radical change. The Milky Way would girdle the heavens as before; some of our familiar constellations, such as Orion, would be little changed, though others would be greatly altered by the shifting of the nearer stars. An unfamiliar brilliant star, between Cassiopeia and Perseus would be—the Sun. Looking back at it with our telescopes, we could photograph its spectrum, observe

its motion among the stars, and convince ourselves that it was the same old Sun; but what had happened to the rest of our planetary system we would not know.

For the planets are so small, in comparison with stellar distances, and shine so feebly by reflected light, that even the best of them would be hopelessly invisible. Jupiter itself would be too faint to be seen at all, or even photographed, with a hundred-inch telescope. A two-hundred-inch aperture might barely reveal it, if it stood alone on a dark background; but the glare of the Sun, five hundred million times brighter, and only four seconds of arc away, would drown it out utterly in any telescope which human skill dares even to imagine.

This is fantasy: but it passes over into fact when we realize that our spacial isolation condemns us to utter ignorance whether the stars are attended by planets or not. Mere worlds like ours are far too tiny to be detected, even at the smallest stellar distances. We cannot determine by observation whether systems like ours are common (as we know double stars to be) or rare,—or even whether ours may be unique. Only if some theory of its origin should be well established would we be in a position to estimate the probability that others like it would be found among the stars, if we could only go looking for them.

But our system is not only isolated by its remoteness from the stars: it is so, none the less, by its motion among them. With repect to the average of the nearer and brighter stars, the Sun is moving with a velocity of 19 kilometers per second,—more than twice the

diameter of the Earth's orbit every year,—and all its retinue share in this. The stars too are moving,—rather faster, on the average, than we,—so that, seen from one or another, the motion of our system would differ; but we know of no star from which it would appear to be at rest,—though, of course, at a sufficient distance the motion would seem very small.

Imagine an observer on a neighboring star, or on a planet revolving about it, and suppose too that a planet of our system carried a light bright enough to be seen at this distance. In a year's time he could watch the Earth whirl about the Sun, and be sure of its planetary relation. To do the same for Neptune would take more than a century; but he need not wait so long. During one revolution of Neptune, the whole system moves through a distance more than twenty times that which separates the planet from the Sun. Viewed from a distance, then, the greater and the lesser light would obviously be moving together, while the direction and distance from one to the other slowly altered. It is by exactly the same test that we are convinced that hundreds of double stars are real physical pairs, in slow orbital motion, though they have been watched over but a very small fraction of the whole revolution.

For the comets, which go farther from the Sun and move slower, the evidence (were they visible from afar) would be even more definite; and the results of calculation from terrestrial observations are decisive. The bodies which compose our system share a common motion through space. They are and have been permanent companions; and it is altogether reasonable,

and indeed almost inevitable, to attribute to them a common origin.

But are there no intruders into the family?—no wanderers entering our system from interstellar space? Such an interloper could be recognized at once, since it would have a strongly hyperbolic orbit, and move at a higher speed (*ceteris paribus*) than the rest. No body observable telescopically—asteroid or even comet—has ever shown such behavior. But among the thousands of meteors which daily enter the atmosphere, a considerable percentage are moving so fast that their extraneous origin appears to be well assured. The most reliable data,—those of the Harvard-Cornell expedition at Flagstaff, Arizona,—indicate that about seventy per cent of visible meteors are of this sort.[1] The rest move more slowly, and belong to our system.

Many stars have distant companions, self-luminous but faint, which share their motion in space, and are presumably of common origin. Alpha Centauri itself has such an attendant,—often called "Proxima Centauri" since it is probable that it is slightly nearer than its brilliant associate,—separated from it by 2° 11′ in the sky, and in space by at least ten thousand times the Earth's distance from the Sun. To us it is a tiny speck of the eleventh magnitude; but a similar companion of the Sun, at the same distance, would be visible to the naked eye, and show such a motion in the heavens—mainly a reflex of the Earth's swinging around its orbit—that it could not fail to be recognized. Long and

[1] Harvard College Observatory, Announcement Card 296, March 29, 1934.

careful search has failed to detect any star moving thus along with the Sun. Our system is isolated in motion as well as in position—which is indeed the reason why it may justly be regarded as a system.

Whether there may be dark bodies in the void which isolates us, no one knows. They would be visible only if illuminated by the Sun, and for this they would have to be pretty near. Jupiter, which reflects more light than any other planet, would be conspicuous telescopically (8th magnitude) at Pluto's greatest distance. But at ten times this distance it would be of the 18th magnitude, and though observable with a few great telescopes, would stand a very poor chance of discovery,—and this is less than 1/500 the distance to the nearest star.

The attraction of such a body upon Neptune and Pluto would produce perturbations in their orbits which would probably lead ultimately to its discovery, provided it were a distant planet, and several centuries were allowed for the known planets to reach their least and greatest distances from it repeatedly. But a body of equal size and distance, passing by with stellar velocity, would have only time to produce smaller effects before it receded, and would very probably be missed.

2. Almost all stars or star-systems compete with ours in isolation; but nothing that we know of approaches it in *complexity*. Most stars are single. A considerable minority, at least ten per cent, are double, and some triple or quadruple, but the largest number of bodies so

far known in a single system is six (the bright star of Castor, a visual double with a distant attendant, all three being spectroscopic binaries).

In the solar system, on the other hand, there have been observed:

9 large planets,
26 satellites, belonging to 6 of these planets,
more than 1500 asteroids,
about 1000 comets,
innumerable meteors.

The number of asteroids cannot be given exactly because many of those which are observed are lost again before an orbit can be calculated. Observations with great telescopes would enormously increase the list—if an army of computers were available to work up the results. Baade has recently estimated that the whole number of asteroids (mostly very faint) must be thirty thousand.

As for the comets, several new ones are discovered each year, and at least as many must be missed, owing to unfavorable position in the heavens (near the Sun, etc.). The majority of these have very long periods, and thousands of years must elapse before all their mates come back and are caught. The full number probably exceeds 100,000.

This comparison may not be fair to the stellar systems, since we are too far off to see anything that is not furiously incandescent, and also pretty big; but the complexity of our own system is beyond all cavil.

Two features deserve special attention.

First, the presence of a number of sub-systems, revolving about the planets.

The satellite systems of Jupiter, Saturn and Uranus are miniatures of the planetary system almost complete in detail, and with some additional peculiarities. Neptune is so far away that only large satellites could be observed. The known one is one of the biggest in all our system. There may be smaller ones. Mars, with its two tiny satellites, stands in a class by itself, as does also the Earth, with its relatively enormous Moon. This pair, as Young remarked long ago, is really more like a double planet than an ordinary satellite system.

Second, the existence of two groups of bodies—well called by Chamberlin the "Two Solar Families"—which differ radically in almost every respect,—the planets and the comets.

The two are almost antithetical, as appears from the following table:

Planets	*Comets*
Continuous dense bodies	Diffuse swarms of very low density
Masses considerable (measurable by their gravitation)	Masses too small to measure gravitationally
Form spherical or spheroidal; dimensions invariable	Form often very irregular; dimensions change greatly
Shine by reflected light	Largely self-luminous (though the energy comes ultimately from the Sun)
Orbits nearly circular	Orbits nearly parabolic
Orbit planes nearly the same	Orbit planes at random in all directions
All orbital motions "direct" (i.e. in the same sense)	Direct and retrograde motions almost equally numerous

The contrast between conspicuous regularity and random distribution could hardly be more striking.

Order is characteristic of the planets, chaos of the comets.

The asteroids resemble the planets, except for their small size and negligible mass. Their orbits are more eccentric and more highly inclined, but their motions are all direct. The comets of short period (less than 20 years) also all move direct and in orbits of moderate inclination, though more eccentric than for any but a few of the asteroids. The inner parts of the three great satellite systems (each considered by itself) are thoroughly planetary in character. Two faint outer satellites of Jupiter, and one of Saturn, are retrograde, with large eccentricities and inclinations.

3. We have next to deal with the *dynamical properties* of the system. Most of the numerical data which furnish the tests by which a theory stands or falls come under this category, and it is convenient to collect them in tabular form for the nine principal planets. In Table I the Earth's distance from the Sun, mass, and orbital momentum are taken as standards, for convenience. Otherwise it explains itself. Most of the data are highly accurate, but a few are uncertain. The value given for the mass of Pluto is an upper limit. If it were greater, the planet would show a perceptible disk in large telescopes. The actual mass may be smaller. Pluto's rotation period is quite unknown, and all that can be said for Venus is that it is certainly long (as indicated). It is probably no accident that the three least massive planets show the three greatest orbital eccentricities and the two highest inclinations.

The tabular values illustrate the overwhelming pre-

TABLE I—PLANETARY DATA

	Mean Distance	*Eccen-tricity*	*Inclination to Ecliptic*	*Mass*	*Orbital Angular Momentum*	*Mean Diameter (Miles)*	*Density Water=1*	*Rotation Period*	*Inclination of Equator to Orbit*
Sun	....	....	....	332000	....	864000	1.41	25^{d}	$7^{\circ}.2$
Mercury	0.39	0.206	$7^{\circ}.0$	0.04	0.02	3100	3.8	88^{d}	?
Venus	0.72	0.007	$3^{\circ}.4$	0.81	0.07	7700	4.86	$>20^{d}$	?
Earth	1.00	0.017	0 .0	1.00	1.0	7920	5.52	$23^{h}.9$	$23^{\circ}.5$
Mars	1.52	0.093	$1^{\circ}.9$	0.11	0.13	4215	3.96	$24^{h}.6$	$25^{\circ}.2$
Jupiter	5.20	0.048	$1^{\circ}.3$	316.9	722.	86700	1.34	$9^{h}.9$	$3^{\circ}.1$
Saturn	9.54	0.056	$2^{\circ}.5$	94.9	293.	71500	0.71	$10^{h}.2$	$26^{\circ}.7$
Uranus	19.19	0.047	$0^{\circ}.8$	14.7	64.	32000	1.27	$10^{h}.7$	$98^{\circ}.0$
Neptune	30.07	0.009	$1^{\circ}.8$	17.2	94.	31000	1.58	$15^{h}.8$	29°
Pluto	39.51	0.249	$17^{\circ}.1$	0.2?	1.2?	5000?	4 ?	?	?

ponderance of the Sun's mass, which is 744 times as great as that of all the planets combined. Nothing at all like this is known among the stars. There are numerous binary pairs—double stars in orbital motion —in which the mass-ratio of the components can be determined. The brighter of the two is practically always the more massive, but the extreme disparity so far found is about three to one. It would be quite unsafe to conclude, however, that binaries with much more unequal masses did not exist.

There is a remarkable relation between the mass and luminosity of a star, discovered by Sir Arthur Eddington and brilliantly explained by him on very general principles of physics. To put it briefly, large masses (say a million times the Earth's) must necessarily be luminous stars. To support the enormous internal pressure, the interior must be exceedingly hot. Heat will leak out from it to the surface fast enough to keep the body shining strongly. A mass equal to a hundred thousand Earths will not be so hot inside (other things being equal); less heat will escape, and it will be a star of small luminosity. But for masses less than ten thousand times that of our planet the escape of heat will be too small to keep the surface incandescent. They will be dark bodies. No matter how many of these there may be, revolving about the stars, we cannot detect them.

The assumption is often made that because the components of observed double stars have comparable masses this is a general, if not an invariable, rule in stellar systems. This appears to be a dangerous infer-

ence. We cannot see a close companion of a bright star unless it shines pretty strongly on its own account, and hence we can discover only pairs in which the masses are not too different. There are so many pairs of nearly equal mass and brightness that it is clear that Nature does favor equality among such partners; but it would be quite wrong to conclude that "Nature abhors" a great inequality of mass. We must maintain a strict agnosticism on the subject.

The planetary system, at least, is not unique in this respect, for Jupiter is 12,000 times as massive as its largest satellite, and Saturn 4100. Neptune's satellite, judging by its brightness, must be large, and Nicholson's recent study [1] indicates that its mass may be as much as 1/300 that of its primary. Even the Moon, abnormally big as it is, compared with the Earth, has but 1/81 of its mass. The largest of these satellites are as big as Mercury and almost as massive, so that they begin where the planets leave off.

Among the other satellites of Saturn are the smallest masses which have ever been measured by their gravitation. Mimas, the innermost of them, has but 1/16,300,000 of the mass of the planet. So small a mass could not have been measured except by a happy accident, which permits a part of its attraction on a neighboring satellite to produce a cumulative effect which builds up for years before it reverses in direction. On the astronomical scale, this mass is almost infinitesimal; from the engineering standpoint, it is practically infinite, for it amounts to 3.5×10^{22} grams, or

[1] Publications of the Astronomical Society of the Pacific, 43, 261, 1931.

almost forty million billions of tons—enough to make a ball of rock 180 miles in diameter, or, if crushed to fragments, to cover the whole United States with a layer of débris a mile thick.

We may take this as an illustration of "astronomical magnitudes,"—or better, as showing how weak a force gravitation really is. Only in gigantic accumulations of matter does it rise to importance. Half a dozen of the largest asteroids are more massive than this, but most of them are smaller, and some of the faintest are probably only a mile or two in diameter, and may not weigh more than ten billion tons. Comets, too, are of small mass, astronomically speaking. The contribution of the whole vast number of these bodies to the total mass of the system is negligible.

Second only in importance to the distribution of mass is that of *angular momentum*. This may be roughly described as the "quantity of rotation" in the system, as Newton spoke of ordinary momentum as "quantity of motion." Its importance arises from the fact that it is *conserved*. No internal forces or actions in a system can alter its total amount,—though they may transfer it from one part of the system to another, —and this holds true, *even though the forces involve friction* and degrade energy into heat. Only forces from outside can change it,—and these are negligibly small so long as the system is isolated in space.

For a planet moving in a circular orbit the angular momentum is the product of its mass, its distance from the Sun, and its orbital velocity. If the orbit is elliptical, the component of velocity at right angles to the radius vector joining the planet and the Sun must be

used. As the distance diminishes this increases, and by Kepler's law of areas the product of the two is unaltered, so that the angular momentum is the same,—an example of its conservation. For a remote planet, the velocity falls off, but more slowly than the distance increases, so that the angular momentum per unit mass is greater.

Its actual amount is given by the equation

$$A = m \sqrt{GMp}\ [1]$$

where *m* is the planet's mass, *M* the Sun's, *G* the constant of gravitation, and *p* the semi-parameter of the orbit, that is, half the cross-diameter measured through the Sun at right angles to the long axis. (Figure 1.)

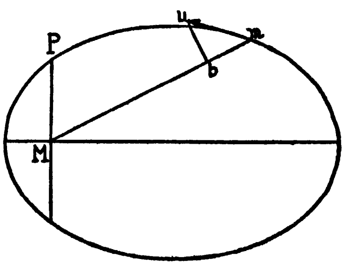

Fig. 1.—Orbit of a Planet or Comet, *mu* is the velocity of the planet, *ub* the component perpendicular to the radius vector *Mm*, *MP* the semi-parameter *p*.

For a rotating body we must multiply the mass of each particle in it by its distance from the axis of rotation, and by its rotational velocity, and take the sum. The result is evidently proportional to the rate of rotation, and to the total mass; but it depends also on the internal distribution of density, for the more the mass is concentrated toward the center the smaller will the average distance of all particles

[1] A small correction, depending on the fact that the Sun is not quite fixed but moves under the planet's attraction, is here ignored, for simplicity. It is insignificant for the present purpose.

within it from the axis be. We may write, in fact, for a rotating body

$$A = m \omega c^2$$

where *m* is the mass, ω the angular velocity, and *c* the "radius of gyration"—the average distance just mentioned. For a homogeneous sphere, *c* is 0.63 times the radius; for a centrally condensed body it is smaller.

The orbital angular momenta of the planets are given in Table I. Jupiter contributes the lion's share, and the four major planets almost the whole total of 1,175 times the value for the Earth. The rotations of the planets, and the motions of the satellites, contribute practically nothing. The Sun's rotational momentum is considerable, but its exact amount is unknown; first, because different parts of its surface rotate at different rates, and, secondly, because though we have no doubt that the density increases toward its center, we do not know how much. If the Sun were homogeneous, its angular momentum would be 40 units of the tabular scale; actually it is probably about 20, but may be less. Fully 98 per cent of the angular momentum of the system is therefore in the motion of the major planets, though they contain but one-seventh of one per cent of the mass.

The satellite systems of Jupiter and Saturn are quite different in this respect; the rotation of the central body provides by far the larger part of the angular momentum. This is undoubtedly true also of Uranus, whose satellites are smaller, and of Mars, with its tiny attendants. The Moon's orbital motion, however, con-

tributes 83 per cent of the total for the sub-system, and the Earth's rotation the remaining 17 per cent, the effect of the Moon's rotation being very small.

The friction of the oceanic tides is continually slowing down the Earth's rotation and diminishing its angular momentum. By the principle of conservation this must reappear somewhere else. For the lunar tides, it goes into the Moon's orbital angular momentum, so that this, and the cross-diameter of the Moon's orbit, must steadily increase,—as Sir George Darwin pointed out. The solar tides, which are smaller, operate similarly to increase the Earth's distance from the Sun, but this effect is numerically negligible, while the other, in the course of ages, has doubtless been very great.

So far we have talked as if all the orbits and equators were in the same plane. When they are not, the angular momentum becomes a vector quantity whose components around axes differing in direction may be calculated by the usual rules. There is always an *invariable plane* representing the average for the whole system, whose position can be altered only by external forces. If the orbit of one planet is, or becomes, inclined to this on one side, that of some other must be inclined in the opposite direction to maintain the balance.

The periods of *rotation* of the members of our system vary widely,—even more than Table I shows. At first glance it looks as if the larger masses rotated the faster, but the Sun's rotation is slow, and the tiny asteroids spin rapidly. Many of them show variations

of brightness, indicating that one side is lighter colored than the other, and thus the time of rotation is found, even though the most powerful telescopes show the body only as a star-like speck. The shortest known period—for the asteroid Eunomia—is $3^h\ 2^m$.

Very rapid rotation is impossible in an astronomical body, for it would make the centrifugal force at the equator greater than the gravitational attraction, and the mass would fly apart. The limiting period, which is that of a satellite revolving in a circular orbit just outside the surface, varies inversely as the square root of the body's mean density. For Saturn it is $4^h.14$, for Jupiter $2^h.96$, for the Sun $2^h.77$, and for the Earth $1^h.40$. Even if the rotation were somewhat slower, the mass would be so distorted by centrifugal force as to be in danger of rupture. Jeans[1] has shown that the risk is serious if the period is half as great again as the limits given above. The actual rotation periods of the major planets are from 2½ to 6 times these limits. Though this does not endanger their stability, it suffices to bulge out the equator so that in Saturn, where the effect is a maximum, the equatorial diameter exceeds the polar by nearly 11 per cent. An asteroid like Eunomia would be near the danger line, were it not that, for so small a body, the cohesion of the rock adds decidedly to the weak gravitational force opposing disintegration. For the Earth and Mars the rotation is relatively much slower, and causes only a small polar flattening: but the Earth's rotation may have been much faster before the tides got in their work. Mer-

[1] *Astronomy and Cosmogony*, p. 259.

cury, Venus, and the Sun rotate very slowly and are practically spherical.

If the Sun rotated as fast as Jupiter it would be in no danger of breaking up; but its angular momentum would be sixty times the present value, and comparable to, if not greater than, that of all the planets together. The remarkable inequality of distribution previously mentioned appears therefore to arise from a slow rotation of the Sun, rather than from any peculiarity of the planets.

Rotation, if fast enough, can be detected in the stars by the spectroscope, since the Doppler shift arising from the motion of one limb toward us and the other away widens the spectral lines. Rotation-periods as short as a day, however, appear to be rare.

The rotation of a number of satellites is revealed by changes in brightness like those of the asteroids. All these, like the Moon, keep the same face always toward their primary. Tidal friction, gone to the limit, affords a rational explanation.

The orbits of the closer satellites are very nearly in the equatorial planes of their primaries. For more distant ones, like the Moon, and Saturn's satellite Iapetus, the orbit-plane lies nearer that of the planet's orbit. The small and distant outer satellites of Jupiter and Saturn have very high eccentricities and inclinations, and some of them are retrograde. Neptune presents the strangest case of all. Its satellite moves in the retrograde direction, and its orbit-plane shows a slow and steady shift which has been proved to arise from the attraction of the equatorial bulge of the planet, whose

equator is inclined about 20° to the satellite's orbit. The planet's rotation can be determined only by the spectroscopic method—measuring the velocity of approach of one side and recession of the other. When Moore and Menzel did this in 1928[1] they found, to their own amazement, that the rotation was unquestionably direct, and opposite to the satellite's motion. The satellite's mass is only roughly known, but it is evident that the forward angular momentum of the planet's rotation must exceed the backward momentum of the satellite about threefold, so that the net rotation of the system, could it be concentrated into a single lump, would be direct. This leaves Uranus quite alone with its inclination of 98° (as if a forward-rotating system had been tipped just more than halfway over).

4. To find the *age* of our system seemed, a generation ago, to be almost beyond the range of speculation, let alone measurement. But the discovery of radioactivity has opened a "royal road" to the goal, and made the determination of great intervals of time trustworthy, as the accurate measurement of parallax has done for great distances in space.

The fundamental principle is now a matter of general knowledge. If we have a quantity of atoms of some radio-active element, such as uranium, we know that a certain small fraction of them will break up every second, expelling an alpha-particle (the nucleus of a helium atom) and changing into atoms of a differ-

[1] Publications of the Astronomical Society of the Pacific, *40*, 234, 1928.

ent sort. These again break up, in the same general fashion but far more rapidly. After passing through a long series of forms—one of which is radium—the atom ends its amazing career by settling down into a stable state—and by this time it is one of lead, while the ejected alpha-particles have become eight atoms of helium. The whole process takes, on the average, about 100,000 years. The rates of radio-active change are quite unaffected by changes in the temperature or pressure, by chemical combination of the atoms involved, or by any other known influences.

If a quantity of some pure uranium compound were to be shut up in a perfectly tight enclosure, for ten million years, 1/637 of the uranium atoms would break up, and an equal number of atoms of lead would appear (neglecting the relatively short-lived intermediate products). The longer it was left, the greater would be the growth of lead, and, from an analysis of the final material, the interval since its enclosure could be determined.

Nature has generously performed this experiment for us—though of course not under quite such ideal conditions. Many igneous rocks are known, in which uranium-containing minerals crystallized from the fluid magma as it solidified. If these minerals are compact, and no extraneous substances such as the almost ubiquitous water have got at them, the inner parts of the crystals very closely imitate our ideal enclosure. Such minerals can now and then be found, and the amounts of uranium and lead in them determined by precise analysis.

The age then follows, provided that we can be sure that all the lead we find has been produced radioactively, and that none was originally present in the crystal. Once more Nature is kind—the uranium-lead is not identical with the ordinary metal, but has an atomic weight of 206.0 as against 207.1 for the familiar kind. It is a pure isotope, while common lead is a mixture of atoms with weights 206, 207, and 208, with small proportions of others. If a careful atomic weight determination upon the lead extracted from our mineral gives an atomic weight of 206, we need not worry about original contamination; if not, we can allow for it.

Thorium, which is also radio-active, and produces lead atoms of weight 208, is found in many of these minerals. Its presence complicates the reckoning, but does not vitiate its results.

The ages of a large number of eruptive rocks have been determined in this way. They show an excellent correlation with the epochs of their intrusion as determined by geologists on the stratigraphic scale. Carboniferous eruptions are some 250 million years old, late Pre-Cambrian 500 million, and the underlying oldest Pre-Cambrian run up to 1500 million years.

Individual mineral specimens, which we may hold in the hand, have therefore lain undisturbed for this vast interval until the miner's pick released them. The Earth's must be older than this; how much older?

The radio-active method again permits an answer. Uranium and thorium are present, in very small but measurable amounts (6 and 15 parts per million) in

ordinary rocks, and so is lead (7 parts). If these rocks, melted or not, had been there for tens of billions of years the decay of the original uranium and thorium would have formed much more lead. The whole observed amount would have been produced in 3000 million years. Any allowance for primitive lead will reduce this.

This does not of course date the Creation; it declares only that the present crust of the Earth has not been in place for more than three billions of years. As particular parts of it have been there for a billion and a half, we have the age, "bracketed," as artillerists say, in a surprisingly satisfactory fashion.

About two billion years ago, or a bit more, Something happened, and the Earth was started on its present career.

The ages of minerals may also be estimated by comparing the quantity of helium entrapped in them with the amounts of uranium and thorium from which it could be produced. Helium, being a very mobile gas, is likely to have escaped, at least in part, from all but the most impervious substances. It is not surprising then, that the ages calculated in this way often come out lower than from the lead-ratio. They are however of the same order of magnitude.

The helium method can be applied to meteorites, especially to the compact masses of iron which fall now and then on the Earth from interplanetary space. Paneth, from a careful study of 24 such bodies, finds an average age of 1600 million years—which is presumably too low owing to escape of helium—and a

maximum between 2500 and 3000 millions. This is entirely independent evidence. These bodies have never been part of the Earth. Most of them were members of the solar system,—tiny independent planets,—and it is fairly probable that a part were visitors from interstellar space. The close agreement of the two determinations of age suggests that Something happened two or three billion years ago not only to the Earth but to the whole solar system, and possibly far beyond.

Then let us look farther afield. There is no time to tell here the whole story how Slipher, photographing the spectra of the spiral nebulæ, found that they were such as would be given by clusters or clouds of stars, and that the lines were shifted by amounts indicating unprecedented velocities of recession, or how Hubble resolved some of the nearer spirals into stars, detected variables among them, and measured their distances, ranging from 800,000 light years upward. Suffice to say that his methods now furnish estimates, trustworthy on the average, of distances of nebulæ up to 130 million light years, and that the red-shift of the lines increases steadily with the distance, attaining amounts corresponding to a velocity of 40,000 kilometers per second. Distance and velocity are proportional to one another, at the rate of 170 km/sec per million light years.

Strömberg's observations of aberration show that the light of these distant nebulæ is still moving at the standard speed—it has not become wearied *en route* —and the general consensus of opinion agrees that

they are really receding from us at these gigantic speeds.

A million years ago they were all nearer, and all in the same ratio, since the present speeds are proportional to the distance. Carrying our reckoning backward, it indicates that about 1800 million years ago *all* the nebulæ were relatively near us and to one another at the same time,—crowded into a small volume of space from which they have receded to their present wide dispersion.

This makes no allowance for transverse motions of the nebulæ. So far as observations go, these might be as rapid as the recessions, without producing measurable changes in their positions in the heavens during the few decades covered by our photographs. But, if this were so, and the nebulæ really moving in all directions in space, there is no reason why some of the fast-moving ones should not be fairly near us. If the motions are really straight away, the fast-moving ones are distant just because they move fast. Our own galaxy may have moved away from its original position, too, but this does not affect the recession of all the nebulæ from one another produced by the general expansion of the "universe" to which they belong.

It begins to look then as if Something had happened to the material universe at large, and the interval since this occurrence agrees with the values found for the ages of the Earth and of meteorites, within the errors of the various estimates.

Strong support for this belief is found in the modern developments of relativity. Einstein's most general

equations applied to the material universe at large admit of a variety of solutions. In some of these, space itself is finite (re-entrant) but is expanding—growing farther round, so to speak, as time progresses—and material objects, such as the nebulæ, carried by this expansion, are receding from one another the faster the remoter they already are. In others, space is infinite, but material systems still recede from one another in much the same fashion. There are other possible solutions—the universe *might* be contracting, but all the evidence indicates that it *is* expanding. The rate of expansion may have been different in the past; the universe may have started slowly to expand from a size smaller than its present, but still very large, as Eddington suggests, or it may have contracted from a very great size, reached a minimum, and expanded again as de Sitter believes; or, again, it may once have been very much smaller than now and expanded at a furious rate for a while before slowing down to its present state, as is supposed by Lemaître and Tolman. It is thus at least possible, though not certain, that when Something happened, a couple of billion years ago, stars, systems, and nebulæ were far more closely crowded than now, so that all sorts of things may have occurred which are exceedingly improbable today. In fifty billions of years or so, if things keep on as they are, the nebulae will have receded out of sight, the radio-active elements decayed, and this will be a dull universe. We may be glad we are here before things have run down, and may meditate profitably on Eddington's suggestion that the two thousand million

years represent "the interval between the event itself and a direct consequence of the event (viz.: the evolution of beings capable of speculating on it)."

But is it reasonable anyhow to assume that the Sun itself has kept on shining for so long a time? Here recent developments in astrophysics provide us with a definite answer. The Sun is radiating energy at a known rate: this, like all other forms of energy, has mass, and the rate of loss of mass by the Sun is easily calculable. It amounts to no less than 4,200,000 tons per second; yet at this rate the Sun would lose but 1/15,000 of its whole mass in a billion years. Transmutation of atoms of one species into another, and especially of hydrogen into heavier atoms, could supply far more than this amount of energy, with the corresponding loss of mass. So there is no difficulty at all in believing that the Sun has been shining for billions of years, and may shine for billions yet. What is more, the Sun has probably changed very little indeed in brightness and size as well as in mass, since the Earth was new. As has already been mentioned, a star's mass practically determines its luminosity. So far as this theory goes, the star might be of any size, but observations show that stars of the Sun's mass and brightness are also—without exception as yet—very similar to it in size. Just why this should be is not yet known—though it probably depends on the laws of the energy-liberating process in the very hot interior of the star. But there can be no doubt of the fact; and we are not merely permitted, but impelled, to assume that, at the time when the Earth was born, the Sun was sub-

stantially of its present size, mass, and temperature.

5. In a system as old as this the question of its *stability* in the past must be considered. The gravitational interaction of its members presents no easy problem. Fortunately for the investigator, the hordes of asteroids and comets have such small masses that the influence of their attraction upon the motion of the planets is quite negligible—though the reverse is very far from true, as we shall soon see. But, with nine planets and the Sun, we have still a problem of ten bodies—and even the problem of three bodies (that is, of their motions under the law of gravitation) is of extreme mathematical complexity and practically insoluble in general terms.

The smallness of the planets saves the situation, for their mutual attractions are small and that of the Sun on each one is dominant. We can therefore solve by successive approximations, treating each planet at the start as if the others were not there, and calculating an approximate orbit; calculating the positions of the planets from these, and so getting approximations to the "disturbing" forces due to their attraction. The effect of these attractions on the motions of the planets can then be calculated, getting more accurate values for their positions at any time. From these again come more precise values of the disturbing forces, and so on.

The process, though very laborious, is fairly convergent in practice. Even for Jupiter and Saturn, where the second approximation improves a good deal

upon the first, the third alters the results so little that we may rest content with it, and the resulting tables of the motion of the planets give a satisfactory agreement with observation.

The results of this analysis may be expressed by supposing that each planet moves in an elliptic orbit of slowly varying shape and inclination, but, as compared with an imaginary body following this orbit according to Kepler's laws, is set forward or back, up or down, out or in, by amounts which continually vary but are always small. The latter periodic perturbations do not concern us here, but the slow "secular" changes in the orbits are a different matter. If they continued indefinitely in the same direction,—for example, if the eccentricity of an orbit continually increased,—they would in time alter the system radically.

But the next step in the analysis indicates that these gradual changes themselves may be represented by the combination of slowly moving periodic effects. The orbit plane shifts this way and that, but its inclination to the invariable plane never exceeds a moderate limit. The center of the orbit, though not coincident with the Sun, never gets very far from it. Most important of all, the diameter of the orbit, and the period of revolution, remain unchanged. The general character of the orbital system, then, remains the same; only the details vary. The theoretical limits of eccentricity and inclination are greater for the small masses than for the large,—in accordance with the observed distribution.

Were these conclusions derived from an exact ana-

lytical solution, the stability of our system would be demonstrated (so far as gravitational forces go). But the calculations involve approximations, and the quantities neglected in these, though very small, may have a cumulative effect, which, after a long interval of time, becomes important.

Professor E. W. Brown, who speaks with the highest authority on these matters, concludes that the results of the approximate theory regarding the planetary orbits are to be trusted over an interval of a hundred million years, but not for a thousand million. In so long a time, the orbits may have altered greatly, especially in eccentricity and inclination. The mean distances and periods are much less liable to alteration, but even these may have changed.

Within a very long time interval, there will be periods—perhaps millions of years in length—during which some of the orbits are highly eccentric and inclined; but this should be a rather exceptional condition, and, for most of the time, the eccentricities and inclinations should be moderate.

The asteroids, which are relatively near to the massive Jupiter, are subject to greater perturbations. It has long been known that there are none of them with periods just equal to one-half or one-third that of Jupiter. These gaps probably represent situations in which a planet's orbit would remain for a relatively short portion of the long interval just discussed. Among the others, Hirayama has discovered several "families" such that the members of each have nearly equal periods, and orbits inclined by almost the same

amount to that of Jupiter. This arrangement suggests the old hypothesis that they were once parts of a single mass, which was disrupted in some way, without dispersing the fragments very violently. Brown considers, however, that these groups may represent situations in which an orbit, fluctuating throughout the ages, is likely to remain long.

Such stability as the planetary system possesses depends doubtless upon the smallness of their masses. Many multiple stars are known, but no case has been found in which the period of one attendant is only two or three times that of another, as is familiar among the planets. Instead, close pairs of short period have distant companions (perhaps themselves double) revolving about the combined mass in a period many times longer.

The main parts of the satellite systems have probably about the same degree of stability as the planetary system—indeed, their continued existence almost compels this belief. The tiny, remote, retrograde satellites of Jupiter and Saturn are quite another story. The idea that they are "captured" asteroids—diverted from orbits around the Sun into paths encircling the planet—suggests itself; but analytical study shows that no such capture can have occurred in recent times,—that is, within many thousand revolutions. Whether it may have occurred in the remote past is unknown.

The most curious feature of the whole system remains to be mentioned. Saturn's rings appear telescopically as an immense circular disk, with concentric divisions. They are perfectly flat and extraordinarily

thin, their thickness being less than 1/20,000 of their diameter. It has been known for many years, from remarkably varied and decisive evidence, that they are composed of a host of tiny satellites swarming so thickly in the denser parts that they appear as bright as a continuous white surface, but scattered in the outer and inner portions so that the ball of the planet is faintly visible through the interstices. Their aggregate mass is small,—probably not more than that of one of the smaller satellites.

Maxwell, in 1859, proved that such an assemblage of satellites would be stable, provided they were small enough, despite their mutual attractions. The divisions in the rings correspond to periods of revolution which are just ½, ⅓, ⅗, etc. of those of the innermost satellites, so that they are probably analogous to the gaps in the distribution of the asteroids.

Were the matter composing the rings gathered into a single satellite, it would be unstable, but in a manner not previously discussed.

Imagine a satellite to be brought nearer and nearer to its primary, by slow changes, in a nearly circular orbit. As it approaches, the tidal forces, arising from the differences in the planet's attraction on the nearer and farther sides of the mass, rapidly increase, while its own gravitation is unaltered. Before it reached the planet's surface, the tidal force, which tends to pull the satellite apart, would exceed its own attraction; and, if liquid, and free to change its shape, it would break in two. The fragments would be subject to smaller tidal forces, but their gravitation would be

more feeble, and they, too, would undergo fission, the process continuing until terminated by molecular forces, like the surface tension which causes water to round itself into drops. A solid mass would be harder to disintegrate; but, the larger it was, the greater would be the disruptive force per square inch, to which it was exposed, and only very small bodies, astronomically speaking, could survive.

For a satellite of the same density as the planet, the critical distance at which it would begin to break up is 2.44 times the planet's radius (as Roche showed in 1850). The whole of the ring-system is inside this limit, while all the known satellites, of the other planets as well as Saturn, lie outside. The conclusion that the rings represent one or more satellites "spoiled in the making" appears to be reasonable.

The effects of tidal friction in slowing down the Earth's rotation and increasing the Moon's distance have already been mentioned. At the present time the day is increasing in length by 1/1000 of a second per century. So small a change is detectable only by its cumulative effect over many centuries, but Fotheringham's masterly discussion of the records of ancient eclipses has put its existence beyond question.

Minute as it seems, the braking action demands the continuous dissipation of energy at the rate of 2100 million horse-power. Jeffreys and G. I. Taylor have shown that the actual friction of the tidal currents, especially in Bering Sea, is actually of this order of magnitude.

As an inevitable result of this retardation, the

Moon's distance increases—the calculated rate being six-tenths of an inch per year. In remote ages, the Moon must have been nearer, and both the month and the day shorter. At the limit, counting backward, the Moon was about 8000 miles from the Earth (center to center) and the day and the month both equal to four hours of our present reckoning. How long ago this was we cannot tell, for the rate of tidal friction depends on the extent of shallow seas, and hence on unknown details of paleogeography. In a still more remote future, another limit might be approached, with the day 47 times as long as at present, and equal to the month.

Neptune's satellite presents a curious case. Since it is moving in the opposite sense to the planet's rotation, tidal friction, slowing the latter, would diminish the numerical value of the satellite's angular momentum, and bring it nearer the planet, till ultimately it comes inside Roche's limit and breaks up into a gigantic ring-system. We can easily enough calculate the height of the tides raised on Neptune by its satellite; but how much friction they produce we cannot even guess,—though it is likely to be small, as the outer parts of the planet are probably gaseous.

At long last, the solar tides might slow the rotation of the Earth till the day was longer than the month, and the Moon would then begin to come nearer, and might theoretically meet the same fate. But the Sun itself may grow cold before this happens.

Comets are liable to much greater vicissitudes than the planets. The primary effect of perturbative attrac-

tion is to change the velocity of a body. If it is moving in a roughly circular orbit, a small change in velocity will alter the orbit but little. A parabolic orbit, however, represents a critical case. If the velocity is decreased, ever so little, the orbit will become elliptic and the body will return to the Sun at regular intervals (if not further disturbed); if the velocity is increased, the orbit becomes hyperbolic, and the comet recedes, never to return, and much more rapidly than it would have done in the original parabola. If the perturbation happens near perihelion, the part of the orbit near the Sun will not be greatly altered, but the extent, or even the character, of its remoter portion may be radically changed.

Even though a comet does not pass close to any of the planets, the cumulative effect of their attraction may be considerable. Halley's Comet, for example, has been observed at the last 27 returns. Its average period is 77 years, but the separate intervals have ranged from 74½ to 79½, in exact accordance with the calculated influence of the planets. The average change in period from one revolution to the next is 1½ years. This corresponds to an alteration of the orbital velocity, at the Earth's distance from the Sun, of 25 feet per second—the velocity itself being 26 miles per second.

The same change of velocity in a comet with a period of 10,000 years would increase it to 18,000 or decrease it to 6500. This is a fairly representative case; and we may conclude that such comets return to the Sun at very unequal intervals.

An acceleration a few times greater than this would change the comet's orbit from an ellipse to a hyperbola, so that it disappeared into interstellar space, never to return. The chance that such an estray would pass near enough to another star to be counted, even temporarily, as belonging to it, is vanishingly small. Our system therefore suffers from a steady and irretrievable loss of comets, and must have been much richer in them in the remote past.

No cometary visitor from outside it has ever been recorded. Several comets, while near the Sun, and bright enough to be seen, moved in definitely hyperbolic orbits; but in every case the excess of their velocity above that requisite for a parabola was small, and calculations have shown that it was produced by the attraction of the planets as the comet came in. All these comets, when well outside Neptune's orbit, approached the Sun in elliptical paths—that is, every one was returning after a previous visit to the Sun, and probably an indefinite succession of them, and was definitely a member of the solar system.

A comet may, of course, be retarded by planetary attraction, transforming its orbit from a parabola to an ellipse, or from an ellipse of long to one of shorter period. A large effect can be produced only if the comet comes close to a massive planet. The new orbit passes through the region where the perturbation occurred—that is, close to the orbit of the disturbing planet—and so gives circumstantial evidence of the encounter. All the comets of short period,—less than ten years or so,—pass close to Jupiter's orbit, and there is little doubt

that they have been diverted into their present orbits by his attraction.

In two cases, Lexell's Comet of 1770 and Brooks' Comet of 1889, the date and circumstances of the encounter are known. The former after two revolutions came close to Jupiter again, and was sent so far from the Sun that it has never been seen since. The latter is still pursuing its new orbit. It has been shown by H. A. Newton that a comet thus captured is far more likely than not to have a direct motion and a small inclination—as all the short-period comets actually do.

There is no danger of such an encounter between any of the principal planets. But Pluto's perihelion distance is less than Neptune's. As their orbits shift, it is possible that, at some future time, the two may come close together. The orbit of Pluto might be considerably modified by such an encounter; Neptune, with its greater mass, would suffer much less.

A few asteroids, notably Eros, may have undergone similar orbital changes in the past, or meet them in the future, by close approaches to Mars.

Even when a comet has receded far beyond the range of disturbance by the planets, it is still in trouble, for the attraction of the stars upon it begins to tell. If the Sun and stars were fixed, a comet which receded more than halfway to a neighboring star would fall under its predominant influence, and never return to us. But the stars are moving very much faster than a distant comet moves relatively to the Sun, and any particular one will get by and recede before it has time to disturb the comet's motion

greatly, unless it comes pretty near it. On this account the region within which a comet may move, without running any great risk of being diverted away from the Sun during two or three billion years, extends to a distance of some fifteen light years—far beyond the nearest stars.[1] To go to this limit and return would take a comet about 300 million years, so that even the remotest members of our system have had time to complete several revolutions since their origin. Though such a comet would probably return to the Sun, it would stand a very poor chance of coming near enough to it to be seen again from the Earth. Its orbit, plotted on any ordinary scale, would look like a straight line receding from the Sun and returning again. During all its long flight, the attraction of the stars would be pulling it sidewise, more or less; and this tends to widen out the orbit and increase the perihelion distance. Almost all comets are invisible when they are at more than three or four times the Earth's distance from the Sun; so it would not take very much to cause one to be lost to sight, though not to the solar system. Öpik calculates that a comet with a period of more than a million years stands a poor chance of remaining observable, after the thousand or more revolutions which it has made. This type of loss, however, is not irrevocable. Stellar attraction may, by chance, change the orbit back to a small perihelion distance and bring the comet again into view,—though this is not very likely. For periods less than 30,000

[1] E. Öpik, "Proceedings of the American Academy of Arts and Sciences," *67*, 169, 1932.

years the attraction of the stars is unlikely to produce great effects.

The orbital inclinations, too, are subject to change by stellar perturbations. The effect, in the long run, is to mix them up at random, and it may be that the observed indiscriminate distribution of cometary inclinations is thus to be explained.

This does not exhaust the list of the comet's tribulations. Many of them may escape diversion by the attraction of the planets or the stars, but none of them can avoid another disintegrating force.

When light, or any other electromagnetic radiation, falls on a material body and is reflected, scattered, or absorbed, it exerts a pressure upon the surface which it meets. The pressure is minutely small. For full sunlight, at the Earth's distance, it amounts to 4.5×10^{-5} dynes/cm^{2} or 1/16 of an ounce per acre. The effects of this upon the planets, or even on the smallest asteroid, are utterly negligible. Even for a stony meteorite a centimeter in diameter, the Sun's radiation pressure is but 1/24,000 of its gravitational attraction. For free dust grains, 1/100,000 of an inch in diameter, the radiation pressure equals the attraction, and for smaller ones it prevails so that they are actually *repelled* by the Sun. Since both forces vary as the inverse square, this is true at all distances.

When the circumference of the particles is much less than the wave-length of the radiation, it gets a feebler grip on them, and the pressure falls off, so that they are again attracted; but there is an intervening range of size within which the net repul-

sion may be several times the normal gravitational force.

Individual molecules or atoms, provided they absorb radiation of the kind which the Sun emits strongly (roughly speaking, visible light) are subject to powerful radiation pressure, and may be violently repelled from the Sun.

The forms of comets' tails, and the motions of luminous condensations within them, which have often been photographed, show that they are composed of matter emitted from the comet's head, and acted upon by some force, directed away from the Sun, which imparts ever-increasing velocities. The eruptive prominences—masses of exceedingly rarified gas—which are sometimes observed to rise from the Sun to heights as great as 500,000 miles, and at speeds increasing to 100 or even 250 miles per second, are undoubtedly set in motion by the same force. In both cases, though very high velocities are attained, only a very small quantity of matter is moved. A sheet of tissue paper, 1/1000 of an inch thick, would be thirty times too heavy to be lifted by the Sun's radiation pressure against its attraction.

The material of the tail never returns to the comet, but is dispersed into space quite as thoroughly as the smoke of a steamer, carried by the wind, vanishes into the air. When the comet is receding from the Sun, the tail runs in front of it, like smoke in a following gale.

Comets, especially the more conspicuous ones, are therefore steadily wasting away, and must have a limited life as luminous bodies. It is only when near the

Sun, however, that they are thus active. At a distance of more than 200 million miles from the Sun, even great comets have no tails. As they come nearer, and the swarm of meteoric masses which forms the nucleus is warmed by the Sun's increasing radiation, gas begins to ooze out from them, carrying perhaps fine dust with it, and the gas-molecules and dust-particles are repelled by radiation pressure to form the tail. The escape of gas, and the length of the tail, are greatest just after perihelion passage, when the nucleus is hottest. Then it cools down, and, after a few months, activity ceases, perhaps for thousands of years, till the next return.

How often this process may be repeated, we do not know. Halley's Comet has been seen to grow twenty-seven successive tails—all long and conspicuous—during the past two thousand years, and shows no sign of exhaustion. The other comets of comparable period, however, are much less prominent, and those of short period, which return frequently to the Sun, have usually no tails at all. One of them, indeed—Biela's Comet—which was fairly conspicuous in the early part of the 19th century, and was observed at several returns at intervals of 6¾ years, has not been seen at all since 1852. It has simply faded out, and one or two other short-period comets appear also to be lost. The majority of them seem to be longer lived, but it is probable that there would be no short-period comets to observe if their number was not being recruited by captures by Jupiter. One such case is known to have occurred in the 18th century, and one in the

19th. Since the number of known short-period comets is about fifty, and some of those captured may be lost again by the reverse process, it would appear that even these faint comets must last, on the average, for some 5000 years, that is, for about a thousand returns to perihelion, before their luminescent matter becomes dissipated.

If Halley's Comet, however, has been pursuing its present orbit since late Pre-Cambrian times, it must have grown and lost eight million tails—which seems improbable. According to Schwarzschild's calculations the tail of this comet, in 1910, if composed entirely of gas, may have contained as little as 100 tons of matter; if formed of dust, it may have amounted to a million tons. Several times this amount streamed along the tail during this apparition.

Eight million tails would thus demand enough gas to form a liquefied sphere of a mile and a half in diameter, or a 25-mile ball of compressed dust. The material lost in the tail is probably but a small fraction of the comet's mass. Now in 1909, when Halley's Comet was first caught on its way in, it showed a continuous spectrum, and had not begun to grow any gaseous envelope; its brightness indicated that the total reflecting area of the bodies of which it was composed was about 500 square miles—scattered in small patches over a region 14,000 miles in diameter. The total volume of the particles was probably much less than 500 cubic miles, so that they cannot possibly have held enough dust to make all these tails, and probably not enough gas.

It is more probable that the comet has been diverted into its present path, from one of much longer period, at some much less distant time, and has not yet worn out. Its orbit does not now come near any of the great planets, so that its capture can be no recent event; but the accumulation of ordinary small perturbations during a few thousand revolutions would probably suffice to shift the orbit enough to remove all traces of the original point of capture.

We are here faced with a serious dilemma. Comets with periods exceeding about 50,000 years are liable to be lost to our system by planetary perturbations near perihelion, and, to a lesser degree, by stellar perturbations near aphelion. Those of shorter average period, however, must have returned to the Sun tens of thousands of times during the known age of the Earth, and should therefore be thoroughly worn out.

Bobrovnikoff has therefore suggested that the existing comets have been added to the system by capture while the Sun was passing through a nebula, or some sort of cloud of diffuse matter, a million years or so ago. This relatively recent date is derived from an estimated rate of disintegration of short-period comets, several times more rapid than that made above; but a tenfold increase would leave the comets very young indeed in comparison with the planets. If the hypothetical nebula was independent of our system, the latter must have passed through it with considerable velocity. A vast majority of the comet-forming clusters of matter would have had hyperbolic orbits, and only those which were captured under special circum-

stances would have been retained as members of the system. As these still number hundreds of thousands, the density of the parent nebula must, on this hypothesis, have been great.

An alternative possibility, following Öpik's suggestion, is that comets are as old as the Earth, but, that, for most of their history, they have been following orbits with considerable perihelion distances—greater, say, than Jupiter's—and so have escaped tail-formation and depletion, and, incidentally, been invisible. Those whose orbits have been altered, whether by planetary or stellar perturbations, so as to bring them nearer the Sun, furnish the visible, and occasionally conspicuous, bodies which are now observed, and may continue to be observable for millions of years, though hardly for billions.

The chief difficulty about this hypothesis is that it demands the existence of an enormous number of comets of large perihelion distance,—though this is no worse than the assumption which had to be made about the nebula on the alternative theory. Neither hypothesis can be tested by observation.

II

PHYSICAL AND CHEMICAL PROPERTIES OF THE SYSTEM

HAVING considered the positions and motions of the members of our system, we may now turn to the bodies themselves, and ask what is known of their nature and composition.

1. The earliest available information of this sort came from the *densities* (Table I). The four terrestrial planets, and also the Moon, have mean densities ranging from 3 to 5½ times that of water, while the average for ordinary rocks is about 2.7. The mountainous surface of the Moon, with its low reflecting power and general brownish color, is evidently composed of rock, and we may safely assume the same for the rest. The central regions of the larger ones, like the Earth and Venus, must be much denser, to make up the average. The largest planets of the group are the densest, owing probably to the compression of the interior by the great weight of the overlying material. Pluto, we may reasonably guess, is of the same general character. The densities of the major planets, especially Saturn, are so low that their rocky cores, if they exist, must be many thousands of miles below the visible surface.

There is fortunately a way of testing this conclusion.

The rapid rotation of these planets causes them to be flattened at the poles. The amount of this ellipticity can be determined by direct measures, or by perturbations which it produces in the orbits of the satellites. Its theoretical amount depends on the mean density and the rotation period, and also on the extent to which the density increases toward the center—being greatest for a homogeneous mass.

In this way it is found that Mars is of nearly the same density throughout, the Earth more condensed, so that its central density is nearly twice the mean. Jupiter still more so, and Saturn most of all. Uranus and Neptune are much like Jupiter, as might be expected from their similar mean densities.

If we assume that the central core is as dense as the Earth—which, considering the enormous pressure to which it is subjected, is conservative—we find, following Jeffreys, that the data for Saturn are satisfied with a core 32,000 miles in diameter surrounded by a shell 20,000 miles thick, of density 0.26 times that of water. This is on the assumption that the outer layer is homogeneous; actually, the superficial portions must be of much lower density, and therefore gaseous.

The pressure at the bottom of the shell is fully a million atmospheres. A thousandth part of the way down—measured by the quantity of material passed through—it would already be great enough to compress any gas to nearly the density of the corresponding liquid.

Now all known gases, when liquefied, have densities greater than 0.3, except hydrogen (0.07) and helium

(0.12). It appears, therefore, that Saturn must have a huge atmosphere, thousands of miles deep, composed mainly of these lightest gases,[1] highly compressed.

For Jupiter, the mean density of the outer layer comes out 0.76. The outer parts must be gaseous, and of low molecular weight; but their composition cannot be so closely specified. The same may be said of Uranus and Neptune.

Saturn's principal satellite, Titan, and the inner two of Jupiter's prominent four, have densities ranging from 2.6 to 3.5 times that of water, and are doubtless spheres of rock like the Moon—which they resemble in size and mass. The density of Jupiter's third satellite is 2.2 and of the fourth 1.3. They must be cold, like the planet, and Jeffreys' suggestion that the latter is composed largely of ice seems reasonable. Its albedo (reflecting power) is low—but a very thin coating of dust would suffice for this. Some of Saturn's inner satellites are surprisingly bright, in proportion to their masses, and must have large surfaces and low densities, even if they are as white as snow—unless, indeed, the measures of their brightness (which are very difficult) are in error.

It would be of great interest to determine the degree of internal concentration in the Sun: but its rotation is so slow that no perceptible ellipticity results. Different theories of its internal constitution lead to very different conclusions: Steensholt's "model" has very little central condensation; Eddington's much

[1] R. Wildt, *Göttingen Nachr.* N.F. *1*, 67, 1934.

more than Saturn; while Milne's involves a small core of exceedingly high density. It is not possible at present to decide among them. A test may come before long from the study of eclipsing double stars, but the problem is intricate.

2. The *temperatures* of the Sun and planets—that is, of their surfaces—may be found by measurements of the heat which they radiate in different wavelengths. From these we can find the "effective temperature"—that is, the temperature of a perfect radiator, or "black body" [1] of the same size, which sends out radiation of the same amount, or quality, as the case may be. The actual temperature may not be the same, but is rarely likely to be very different.

For the Sun various methods, based on the total amount of the radiation, or on the relative proportion of that of long and short wave-length, give effective temperatures ranging from 5800° to 6300°. The round number 6000° K (measured on the Centigrade scale from the absolute zero at —273°) may be adopted for most purposes. The actual temperature varies with the depth, from about 5000° in the upper levels of the Sun's atmosphere to 7000° or more in the deeper regions which are almost hidden from us by the haziness of the overlying gases.

Deeper in the Sun's interior the temperature is very high. Eddington's theory gives a central temperature

[1] This curious name arises from the theoretical conclusion that a perfect radiator would also be a perfect absorber of incident light, and would therefore appear absolutely black at ordinary temperatures.

of 30,000,000°; Milne's indicates one many times greater. The various theories agree that all but a very small fraction of the Sun's mass is at a temperature exceeding a million degrees.

The radiation from the planets, and even from selected portions of their surfaces, can be measured with great telescopes and sensitive thermocouples. There is no great difficulty in separating the reflected sunlight from the long-wave radiation emitted by the planets themselves. After a troublesome correction for the absorption of the latter in the Earth's atmosphere the temperatures of the planet's surface can be calculated. They are in all cases near to the values which might be expected for bodies which derive all their heat from the Sun.

The illuminated side of Mercury, which permanently faces the Sun, is very hot, about 400° Centigrade. The sunlit side of Venus reaches 50° or 60° C (above the ordinary, not the absolute, zero) while the dark side falls to —20°. The Moon can be studied in detail. During the middle of its long day, which lasts a fortnight of our time, the temperature of the surface rises to 120° Centigrade,—hotter than boiling water. During the long lunar night it falls to about —150°. This enormous range illustrates the abject dependence of planetary temperature upon solar radiation. During a lunar eclipse (January 14, 1927) observed by Pettit and Nicholson, the Moon's surface cooled from 70° to —80° Centigrade in a little more than an hour, as the Sun's light was cut off by the interposition of the Earth, and dropped 40° more during the 2½ hours in

which the Sun was hidden from the region under observation. With the Sun's returning rays it rose in an hour to almost its original value. Those rapid changes show that the cooling was only skin deep, and that the superficial material of the Moon must be a very poor conductor of heat—much worse than any sort of solid rock, and comparable to pumice, or volcanic ashes. While the surface is hotter than boiling water, or almost as cold as liquid air, the temperature a foot below probably varies but a few degrees from an average near the freezing point.

The Earth is protected from these terrific changes by its atmosphere and oceans, which store up great quantities of heat, slow up its escape back into space, and transport it from place to place. Its relatively rapid rotation, by itself, would not preserve it from changes as great as those on the Moon during an eclipse.

The moderate range observed on Venus, despite its slow rotation, may be attributed to the atmosphere which the planet is known to possess.

For Mars the temperature of the hottest regions—the equator at noon, and the south pole during the middle of its summer—runs up to 20° Centigrade but falls far below zero at sunrise and sunset.

The outer planets are very cold. The average temperature of Jupiter's surface comes out —140°, and of Saturn's below —150°. The radiation from surfaces as cold as this is almost too small to measure, so that those values are only approximate. Uranus gives no measurable radiation, and must be colder. Neptune and Pluto are doubtless colder yet.

It was formerly supposed that the major planets might be very hot inside, and hot even at the surface. The total disappearance of Jupiter's satellites in the planet's shadow shows that his surface is not self-luminous; but this would be consistent with its being nearly red-hot. The heat-measurements, however, disprove this absolutely. If the temperature of the surface was that of the coldest Siberian winter, it would, even then, send us many times as much heat as it actually does.

The interior may still be hot, like the Earth's; but the visible surfaces, and probably the interior for some distance below, are certainly very cold. This limits the composition of their atmospheres to the "permanent" gases. Water vapor, for example, must be completely frozen out of the atmosphere, and the ever-changing cloudy forms on Jupiter's surface must be composed of some far less easily condensible substance.

Comets must undergo very great changes of temperature. At aphelion, the remoter comets must be cold enough to freeze anything but hydrogen and helium; at perihelion those which come close to the Sun, like the great comet of 1882, must be hot enough to melt platinum.

3. *Atmospheres* may be detected on the planets in many ways. The rapidly changing markings on Jupiter are evidently clouds, and also the much rarer ones on Saturn. Venus, when between us and the Sun, shows conspicuous effects of twilight. Under favorable circumstances she has been seen as a luminous ring—the at-

mosphere shining out all around the dark side of the planet. Rapidly changing cloudy markings have been photographed on her surface with ultra-violet light. Mars shows occasional clouds, and twilight effects, despite much less favorable geometrical conditions for observing them. Above all, the shrinkage of the white polar caps in the planet's summer, and the simultaneous formation of a cap at the opposite pole, can be explained only by transport of vapor through an atmosphere. All the evidence indicates that this atmosphere is thin. The measures of temperature make it practically certain that the caps are really composed of snow—which, however, may evaporate in a dry atmosphere of low pressure, well below the freezing point, to come down as hoar-frost at the other pole. For Uranus and Neptune—not to mention the Sun—the existence of atmospheres is proved by the spectrum.

Yet the Moon shows no trace at all of atmosphere, though our opportunities of detecting one are far better than in any other case. Mercury may have a very thin one (observers disagree). The reason is now familiar. The molecules of any gas are flying around at high speed in all directions. They would fly away from any planet into space if its gravitation did not pull them back. It will do so for any particle, large or small, whose speed is less than a certain "velocity of escape," but all faster ones will be lost unless something hinders their motion. If the average molecular velocity were equal to the escape velocity, the gas would obviously diffuse away immediately. Even if the escape

velocity is considerably the greater, there will be a steady loss of the faster moving molecules from the upper layers of the atmosphere,—where they are unlikely to be stopped by collisions with other molecules.

The number of fast-moving molecules, however, falls off very rapidly as the speed increases. Jeans has calculated that, if the escape velocity is four times the mean velocity of the molecules, an atmosphere should be almost completely lost in fifty thousand years. If the ratio is $4\frac{1}{2}$ to 1, the time of loss is thirty million years; for 5 to 1 it is 25 billions.

The escape velocity from the Earth is 11.2 kilometers per second, while the mean molecular velocity at 0° C is 1.84 km/sec for hydrogen, and less for all other gases. Hence the Earth should be immune from loss. But the escape velocity from the Moon is only 2.4 km/sec, so that it would lose a hydrogen atmosphere almost instantly.

For different attracting bodies, the escape velocity is proportional to $\sqrt{M/R}$ where M is the mass and R the radius. For different gases, the mean molecular velocity varies as $\sqrt{T/m}$, T being the absolute temperature and m the molecular weight. It follows that the Moon, at its observed maximum temperature of 393° K, would lose water vapor ($m = 18$), nitrogen (28) and oxygen (32), but would retain carbon dioxide (48). If during its long career it has ever been much hotter, it would also have lost this and been left without an atmosphere.

Mercury is larger and more massive, but also hotter, so that its lack of atmosphere is intelligible: Mars has

enough gravitational power to retain an atmosphere, but apparently only barely enough: all the larger planets can do so easily. On the other hand, all bodies as small as the Moon, or smaller, should lose their atmospheres completely unless they are kept cold. There is no hope for the asteroids or the smaller satellites; but the great satellites of Jupiter and Saturn, at their present temperatures, could retain water vapor (by a narrow margin) and all heavier gases and vapors. If they were ever hot for a considerable time, they must have lost them.

Comets, with their very low mean densities, could not hold together at all if they were masses of gas, but would immediately begin to expand indefinitely. Anything with an appreciable vapor pressure would evaporate and disappear. The permanent parts of a comet must therefore consist of solid particles, and possibly also of drops of liquid of high boiling point, scattered here and there with wide empty intervals. It is very hard to see how any part of the gases which exude from these, as they grow warm near perihelion, can ever return. Even if the molecules are not driven away to form the tail, they can hardly escape diffusing away into space.

4. We know more about the interior of the Earth than of any other planet. The direct observations, and even the stratigraphic inferences, of the geologist take us down but a few miles; but there are two ways of going deeper. The first is gravitational. If the Earth's surface were smooth, and its internal constitution

equally simple, the direction and magnitude of the force of gravity would vary from point to point in accordance with simple laws. But it is actually very irregular, and the attraction of mountains and other topographic features pulls the plumb line sidewise by amounts which are often—indeed usually—much larger than the uncertainties of observation. When a series of stations have been connected by a precise, nation-wide geodetic survey, the general effects due to the figure of the Earth as a whole may be determined and allowed for, leaving outstanding the influences of "local attraction" at each place. These effects turn out to be smaller than the direct gravitational attraction of the mountains, which indicates that the rocks beneath them are of lower density than elsewhere, so that the excess of mass above sea-level is nearly compensated by a deficiency below. Measures of the intensity of gravity show similar local effects, and lead to the same conclusion. These isostatic adjustments are of great interest and importance to the geologist, but, as they extend only to a depth of sixty miles, and possibly less, they do not concern us at present.

Study of the deeper interior depends on the fortunate occurrence of earthquakes—fortunate, at least, for this purpose. The jar of even a moderate earthquake sets up vibrations in the rocks which run like waves for hundreds of miles along the Earth's surface, and penetrate far into the interior. A great earthquake shakes the whole planet to its very center. The vibrations, emerging thousands of miles away, are recorded by delicate automatic instruments, always at work in

many seismological observatories. There are waves of many types, some traveling as slowly as 2½ miles per second, and some as fast as eight. From the difference of the times at which they come in, the distance of the earthquake focus can be found. Records at two or three stations in different countries suffice to locate it fully, though it may have happened deep beneath the ocean floor, or in a remote desert. Such reports are commonplaces in the daily press.

The observed effects are complicated, indicating that the original waves must have been reflected and refracted in the interfaces between layers of material of different densities, deep in the Earth's interior.

It appears that there is an upper layer about ten miles thick (varying, perhaps, in different regions), a somewhat thicker intermediate layer, and then a great mass of still denser material. The uppermost layer has the wave-transmitting elastic properties of granite, the middle one resembles uncrystallized basalt, while the lower is like the densest eruptive rocks that ever reach the Earth's surface. The granitic layer may be thin or absent under the Pacific.

Far below, 1800 miles down, a much more radical change of properties occurs. The central core, 4300 miles in diameter, transmits waves of compression, but not those of lateral distortion;—in other words, it behaves like a liquid. It is more than twice as dense as the average for the whole Earth, and twelve times as dense as water, and there is excellent reason to believe that it is composed of *molten iron*—probably alloyed with nickel, as in meteorites, compressed by the enor-

mous weight of the overlying rock to fifty per cent more than its normal density, and prevented from cooling by the enormous blanket of material which surrounds it.

The general composition of the Earth, by weight, may be summarized as follows:[1]

TABLE II

Molten iron	350,000	parts
Dense rock	646,000	"
Granite	3,600	"
Sedimentary rock	160	"
Ocean	239	"
Atmosphere	0.85	"
Total	1,000,000	

The last two items are accurate within one or two per cent; the rest are much rougher.

5. The *chemical composition* can be found by direct analysis for terrestrial materials, by spectroscopic methods for the Sun and the stars, and by both for meteorites. The spectroscope gives us also information about the gaseous envelopes of planets and comets.

It is easy, in principle, to determine the composition of the Earth's crust—say the outer ten miles. We have only to analyze a large enough number of typical rock-samples, and combine the results in proportion to the relative amounts of the different kinds, inferred from geological evidence. For the more abundant elements, the ordinary methods of quantitative analysis suffice. Many of the rarer ones are best determined by spectroscopic means.

[1] Data from Jeffreys, *The Earth,* p. 220, and Goldschmidt, *Fortschritte der Minerologie, 17,* 112, 1933.

The comprehensive work of Clarke and Washington shows that ten elements make up more than 99 per cent of the total.

TABLE III

	By Weight	*By Number of Atoms*		*By Weight*	*By Number of Atoms*
Oxygen	46.4	60.4	Sodium	2.8	2.6
Silicon	27.6	20.3	Potassium	2.6	1.4
Aluminum	8.1	6.2	Magnesium	2.1	1.8
Iron	5.1	1.9	Titanium	0.7	0.3
Calcium	3.6	1.9	Hydrogen	0.13	2.7
			All others	0.9	0.5

The inclusion of the ocean would increase the percentage of hydrogen about sevenfold, and that of oxygen slightly. The atmosphere is insignificant in comparison. These figures, however, represent the composition of only 1/300 of the Earth's mass. The great underlying body of dense rock, to judge by the samples which are brought by eruption to the surface, is richer in iron and magnesium, and poorer in aluminum and silicon. The assumption that the core is of composition similar to iron meteorites, though very reasonable, is unproved.

We are thus left in some doubt about the composition of the Earth as a whole.

For meteorites we can obtain a much more representative average, for samples of all kinds are available for analysis. We have only to allow for the fact that 97 per cent of all those which have been observed to fall are "stones," though the "irons," being easier to identify afterward, form half our museum specimens.

The resulting composition is as follows, according to the Noddacks, for a sample of mean density equal to that of the terrestrial planets.

TABLE IV

	By Weight	*By Number*		*By Weight*	*By Number*
Iron	45.7	24.5	Nickel	3.3	1.7
Oxygen	22.3	41.8	Sulphur	1.8	1.7
Silicon	11.7	12.4	Calcium	1.1	0.8
Magnesium	8.5	10.5	Aluminum	0.9	0.9
Sodium	3.8	4.9	All others	0.9	0.8

Iron and magnesium are much higher than in the granites, and the other four rock-forming metals lower, and also oxygen and silicon, while two new elements are abundant,—nickel and sulphur. The former is alloyed with the iron; the latter appears mainly in metallic sulphides—very rare minerals on Earth, at least in the accessible layers. Goldschmidt, who has made a very careful study of geochemical problems, believes that there is a layer of such sulphides, of unknown thickness, intermediate between the Earth's liquid core and its rocky envelope. The question is not yet settled.

The distribution of the less abundant elements in the Earth's crust and in meteorites shows interesting differences.

Some elements are from ten to a thousand times more abundant in meteorites—chromium, cobalt, nickel, germanium, tin, copper, silver, gold, and the platinum metals. Many of these are rather similar chemically to iron. In a mixture of molten rock and molten iron, they would tend to dissolve in the latter.

Goldschmidt calls them *siderophile*—iron-loving. Gold and platinum show the strongest affinity of this type—which is doubtless why they are precious metals, rare in the surface crust. Copper, silver and chromium go by preference into the sulphide minerals in meteorites, and are called *chalcophile*—ore-loving. The rock-loving *lithophile* elements are of quite a different character. Some of them are chemically similar to the principal rock-forming elements. Rubidium and caesium closely resemble potassium, and strontium and barium are very like calcium. Others get into the rocks for curious reasons. Scandium atoms (or rather the charged ions which enter into chemical combination) are of very nearly the same size as those of magnesium and iron. They can therefore slip easily into the lattice-structure of minerals as they crystallize in place of the commoner ones, and get lost there. It is very rarely that scandium is concentrated into any particular mineral, and then only in small proportions. For this reason, it was regarded as one of the very rarest of all elements, and most professional chemists have never so much as seen a specimen. Goldschmidt, by spectroscopic tests, finds that it is often "camouflaged" in familiar minerals, and is really a hundred times as abundant in the rocks as silver,—which, because it tends to collect into local accumulations of ore, is of economic importance. Gallium and germanium, formerly believed to be even rarer, are similarly camouflaged and turn out to be about as abundant as scandium and ten thousand times more so than was supposed a decade ago.

There are other rock-loving elements, which, though actually just as rare, have long been familiar, since they are found in characteristic minerals, especially in the coarse pegmatites which represent the last portions to crystallize of some great mass of molten magma. These have unusually small or large ions, which do not fit in the place of the commoner kinds, and so are left over in the mother-liquor till the end. The radio-active elements, uranium and thorium, are the most important of this group, which includes also the numerous rare earths, and beryllium,—which, unlike the others, has small atoms.

Finally, there is a group of *atmophile* elements, which are not taken up even in the last crystallization of the rocks, but remain liquid or gaseous, and often escape from volcanoes. Hydrogen (in water vapor) and carbon (in carbon dioxide) are the most important of these.

The water has condensed and run into the ocean, and most of the carbon dioxide has gone to make limestones, and so got into the rocks at second hand. The sodium in the sea has probably been washed out of the rocks during geologic time, but there is too much chlorine and boron to account for in this way and they, too, or their compounds, have probably come from volcanic gases.

Here belong, *par excellence,* helium, neon, argon and the other inert gases which do not combine with other elements and have probably always been in the atmosphere. The more abundant nitrogen is chemically so inactive that it should be placed in this group—

though perhaps some metallic nitrides may be dissolved in the iron core.

The helium of natural gas, by the way, is believed to be a product of underground radio-activity and therefore "juvenile" in a more literal sense than the one usually employed by geologists.

To the four groups—which, of course, overlap considerably—Goldschmidt adds a fifth, the *biophile* elements, which enter into living organisms. The most important of these from our present standpoint is oxygen. Ever since green plants began to grow on the Earth, they have been using energy from sunlight to decompose carbon dioxide taken from the atmosphere, and build up the complex compounds which are the ultimate source of all food. The oxygen is turned back into the atmosphere as a by-product.

Free oxygen is a very active substance to be loose in an atmosphere, and it is continually being bound again. Part of the loss takes place by decay of organic materials, which, when complete, liberates carbon dioxide and starts the cycle afresh. But whenever organic remains are buried in sediments, the oxygen cannot get at them, and remains in the atmosphere. The suggestion that the present great supply of atmospheric oxygen has originated in this way is a century old. If it is true, there must be enough organic matter buried in the sedimentary rocks, as coal, oil, oil-shale, and similar materials, to "balance" the oxygen, so that, if it could all be taken out and burned, the free oxygen would be used up. The geological evidence is quite consistent with this. Most of the car-

bonaceous matter, however, is so widely and thinly distributed that there is no fear that it *could* be got out by the most intensive mining.

But the atmosphere is losing oxygen, slowly but steadily, in another way. The weathering processes, by which rocks are broken down into sand, clay, and mud, are chemical as well as mechanical.

The iron in igneous rocks is partially, but incompletely, oxidized,—in technical language, about three-fifths of it is in the form of ferrous oxide and corresponding compounds, to which rocks such as lava owe their dark gray or bluish color. During the weathering process, about half of this is converted into ferric oxide and other ferric compounds, which are responsible for the familiar red, yellow, or brown coloration of residual soil, clay, sandstone, etc. No reverse process is known, and the oxygen thus removed from the atmosphere is permanently lost. The total depletion during geological time must have been very great. Goldschmidt estimates the amount of this "fossil" oxygen as at least as great, and possibly twice as great, as all that remains in the atmosphere. A corresponding increase in the assumed amount of fossil carbonaceous material is still consistent with the evidence. It may well be, then, that the golden sands of the Sahara, and the brilliant crimsons of the Painted Desert, may themselves be signs that life has existed on Earth.

In view of these complications, we can hardly do better in estimating the composition of the Earth as a whole, than to take the simple average for a mixture consisting of equal parts of granitic rocks and

meteorites. The ocean and atmosphere form so small a part of the whole mass of the planet that we may neglect them altogether, except for special investigations.

The main purpose of this long geochemical digression is a comparison of the composition of the Earth and the Sun. The spectroscopic analysis of the latter differs in many ways from the work of the terrestrial chemist. It is done all at once, and not by a laborious series of successive reactions; but the chemist has freedom to devise new and more delicate tests, while the spectroscopist must take what he finds. The surface layer upon the Sun, which alone can be directly studied, is far thinner than on Earth; and the astrophysicist has less to go on than the geophysicist when he attempts inferences about the composition of the interior.

The Sun is the only extra-terrestrial source whose spectrum can be studied in really satisfactory detail. This once, we have plenty of light and can use apparatus of high resolving power, so that the real widths of the spectral lines are not greatly obscured by the widening of the images due to limited optical power.

The classical work of Rowland, forty years ago, gave a substantially definitive account of the part of the spectrum which could then be photographed. The careful revision recently made at Mt. Wilson has added only half a dozen lines to the more than twenty thousand in his tables. The discovery of methods of sensitizing plates for the deep red, and recently for the nearer infra-red, has nearly doubled the range of wavelength available for precise study. The completion

of the extension of Rowland's Table, upon which Babcock is now engaged, will add thousands of lines to the list, and has already led to important discoveries.

Extension into the ultra-violet, beyond Rowland's limit, is, alas, impossible. The Earth's upper atmosphere contains a small quantity of ozone, which exerts an extremely strong absorption for the shorter waves, and cuts off everything beyond 3000 angstroms (three-quarters of the wave-length of the visible violet). The most interesting region of the whole spectrum is thus hopelessly obscured from our study,—for most of the ozone lies so high that no aircraft, nor even pilot balloon, can hope to get above it.

Within the observable region, lines of sixty of the ninety known chemical elements have been identified in the solar spectrum, with two or three more possible, but uncertain. Some, like calcium, give lines of enormous strength; others, like lead, only very faint lines. More than 3800 lines of iron appear, and only one line of cadmium. Sodium reveals itself only by lines of the neutral atom, and barium only by lines of the ionized atom.

Finally, many hundreds of the fainter lines are known to arise from the presence of compounds, not fully decomposed even by the fierce heat of the photosphere.

Yet despite this very careful study, not a single spectral line has been found for several familiar elements—neon, argon, chlorine, bromine, mercury, gold, bismuth, nor for a number of rarer ones, such as rhenium and radium.

This was a great puzzle till within the last ten years,

but the difficulty has been completely cleared as a result of recent advances in the interpretation of laboratory spectra. To make a long and fascinating story short, we now know just what happens to an atom when it emits or absorbs a spectral line. It cannot give out light unless it has been previously loaded up with energy, and put into an "excited" state. Then, after resting—usually for a hundred-millionth part of a second, or so—it goes over into another state, and unloads its energy,—or part of it,—in the form of light of a definite wave-length. If this transition has not completely unloaded it, it may successively undergo others, till it fetches up at the bottom. Absorption lines are produced by the reversal of this process.

For such an atom as iron, hundreds of these excited states are known, and the rules which govern the transitions from one to another have been worked out, explaining thousands of spectrum lines. The important point for our present purpose is that some lines are absorbed by an atom in its unexcited ground-state, and others only by atoms in more or less highly excited states. By a general principle of thermodynamics, only a small proportion of all the atoms will be in excited states—the fraction being smaller, the higher the excitation. At low temperatures, the number of even mildly excited atoms will be very small. With rising temperature, the numbers in all the excited states increase rapidly.[1]

The strongest lines in any given spectrum will then

[1] This statement applies exactly only to a gas in an enclosure of uniform temperature. It is approximately true for a stellar atmosphere, but not applicable at all to an electrically excited gas (as in the familiar neon signs), a comet's tail or a nebula.

be those absorbed by the atoms in the ground-state (or, occasionally in a very slightly excited state)—because atoms in such states are the most numerous. These "ultimate lines" may be picked out by laboratory studies (keeping the vapor of the substance under investigation as cool as possible). They are known for almost all the elements,—and, for obvious reasons, afford the most delicate spectroscopic tests of their presence.

Now some, at least, of the ultimate lines of almost all the metals lie in the part of the spectrum accessible to astrophysical study; but for the permanent gases, and all the other non-metals, they are far in the ultraviolet, and obscured by the ozone. Our spectroscopic tests for the metals are therefore usually sensitive. For some important elements (magnesium, silicon) lines are available which are absorbed by slightly excited atoms, and are fairly sensitive. But for all the non-metals, except silicon, and for a few metals, such as gold and mercury, we must depend only upon lines absorbed by highly excited atoms. Even at the high temperature of the Sun's atmosphere, not one atom in a thousand—sometimes not one in a million—will be so much stirred up, and our tests become rough.

To make things worse, these "subordinate" lines are often in the deep red, or even the infra-red. Oxygen, nitrogen, sulphur, and phosphorus were all missed by Rowland, for this reason,—their lines were there, but in regions inaccessible to him. The phosphorus lines are so far out,—near λ10,000—that they were only found in 1934, by Mr. Babcock, Dr. Kiess, and Miss Moore.

These elements show only faint lines; but they must nevertheless be abundant, for otherwise there would not be enough excited atoms present to produce the lines. The hydrogen lines, however, which are absorbed only by very highly excited atoms, are very strong; hence there must be an enormous amount of hydrogen in the Sun's atmosphere.

For the halogens—fluorine, chlorine, etc.,—and the inert gases—helium, neon, argon,—the excited states lie so high that no reasonable abundance of normal atoms would give enough excited ones to produce observable lines—and none appear. (Helium shows *bright* lines in the spectrum of the solar prominences; but no one knows just how its atoms get stirred up enough to do so.)

The most hopeless case of all is boron, which has no known lines at all in the accessible part of the spectrum! Curiously enough, we have proof, nevertheless, of its presence in the Sun, from the bands (groups of closely packed lines) of boron oxide, which are observed in the sun-spot spectrum. Spots are a thousand degrees cooler than the rest of the Sun, and this drop of temperature permits the compound to form in perceptible amounts. Fluorine is similarly recognized by bands of silicon fluoride (which, being harder to dissociate, appears in the ordinary spectrum). The bands of compounds of carbon, nitrogen, and oxygen are also more conspicuous than the lines of the elements themselves—since their bands are absorbed by unexcited molecules.

One further complication exists: at solar tempera-

tures many atoms lose an electron and become ionized. The spectrum of an ionized atom is quite unlike that which it had when neutral, but has its own ultimate and subordinate lines. Several elements of easy ionization—lithium, rubidium, and indium—are so completely ionized that their lines disappear, except in the spots, where ionization is less. Caesium—the easiest of all elements to ionize—does not appear even in the spots. The ultimate lines of its ionized atoms are far in the ultra-violet, and so cannot be detected spectroscopically in the Sun.

Almost all the failures of elements to show up in our spectrum analyses may be accounted for in one of these ways,—but rhenium, bismuth, and radium all have their best lines where we can get at them, and are not found. These metals must be very rare on the Sun,—as, indeed, they are on Earth.

To turn this qualitative investigation into a quantitative analysis, we must do these things: first, find out how many atoms are needed to produce a solar line of given strength; second, add up the results for the observed lines of each element; third, allow for the unobservable lines in the ultra-violet and infra-red; and fourth, allow for the effects of ionization.

The first of these is the hardest. Theoretically, under ideal conditions, the width of a line should be proportional to the square root of the number of atoms which are actually at work producing it. These conditions can be closely realized, in the laboratory,—for example, with very pure sodium vapor—so that the law has been satisfactorily tested. But, impurities, such as for-

eign gases, widen out the lines in the laboratory, and a multitude of other causes, such as the motion of the atoms due to thermal agitation at the high temperature, complicate the situation in the Sun.

Fortunately, there is a way round this difficulty. There are numerous groups of lines (called multiplets) for which the relative numbers of atoms at work can be calculated theoretically; for example, it is twice as great for one of the yellow sodium lines as for the other. By using hundreds of these groups, Dr. Adams, Miss Moore, and I made a calibration of the arbitrary scale on which Rowland had recorded his estimates of the intensity of his solar lines. Reliable measures of the intensities of the lines will before long replace these rough estimates. Meanwhile, a surprisingly large amount of information can be extracted from them.

The calibration indicated that it took fully a million times as many atoms to produce the strongest lines as for the weakest. Using tables constructed on this basis, it was a very simple matter to carry out the second step. The third was not so difficult as it looks; there are trustworthy equations connecting the number of atoms in the ground state and the various excited states at a given temperature, and, if one could get all the strong lines absorbed by atoms in one of the excited states, and so add up and find the number in this state, the rest was simple. The numbers of neutral and of ionized atoms of a number of elements were thus obtained, and there was then no trouble in allowing for ionization in general. It was found, for example that all but one in 1500 of the sodium atoms were

ionized. Were it not for this the yellow lines of sodium —which are anyhow among the strongest in the spectrum—would be so widened as to run together, as they actually do in some unusually cool stars.

The actual amounts of metallic vapor required to produce even the strongest lines seem absurdly small. The great H and K lines of calcium in the violet—by far the heaviest of all—could be produced by a layer of vapor containing no more atoms than one of air, under standard conditions, one centimeter thick. The whole number of metallic atoms of all sorts is only equal to a one-foot layer of air—and this is spread out in an atmosphere hundreds of miles in depth!

These metallic vapors are mixed with a far greater amount of hydrogen—how much is not easy to measure, for the hydrogen lines are peculiarly subject to disturbing influences which broaden them. By an indirect method—depending on the formation of hydrogen compounds—I have recently estimated that the hydrogen—atom for atom—is 300 times as abundant as all the metals together. Nevertheless, the total mass of gas in the Sun's atmosphere is only 1/2000 of that above an equal area of the Earth's surface.

The mass of the Sun's atmosphere—that is, of the gas above the level at which it becomes too hazy to see down into it—appears thus to be only one fifty-billionth part of the Sun's whole mass, or 1/200,000 of the Earth's. The metallic material in it would suffice only to make a fair-sized asteroid.

Remarkable as these results are, there is no escape from them. The tenuity of the Sun's atmosphere was

proved fifty years ago by Sir Norman Lockyer. Exhibiting to an audience the sodium lines in the solar spectrum, and those produced by passing light through an inch-thick Bunsen flame,—which were stronger—he concluded that there was more sodium vapor per square inch of cross section in the flame (though it certainly formed but a very small fraction of the gas there) than there was in the Sun's whole atmosphere.

The end product of our investigation was a table of the composition of the Sun's atmosphere—a quantitative analysis for 56 elements. The results for the metals ought to be good; those for the non-metals are more uncertain, since very large corrections had to be made in passing from the number of excited atoms to the total number.

It is now of great interest to compare these results (which I obtained five years ago) with those of Goldschmidt's recent extension of the analytical work of Clarke and Washington for the Earth's crust and of the Noddacks for meteorites. Taking the average composition of the last two, and comparing with the solar list, it appears that the spectroscopic investigation makes the abundance of the rarer metals smaller, compared with the common ones, than does the analytical work. Now there is some evidence from other sources that the scale of the spectroscopic calibration may be too extended, and exaggerate the differences in the number of atoms required to produce weak and strong lines. A reasonable correction for this (reducing an estimated factor of 100 to 60) brings the terrestrial and solar lists into good agreement. It then appears

that the relative abundance of the various metals is extraordinarily similar in the Earth and the Sun.

Some of these metals are a hundred thousand times more abundant than others, but when the two lists are compared, there are only four cases out of forty-eight in which one makes a given element more than ten times as plentiful as the other,—and in all four either the spectroscopic or the chemical data are known to be poor.

The fourteen most abundant metals, in the order of the number of atoms present, are as follows. The average abundance for the first group in each column is about ten times that for the second, and this again ten times as great as for the third.

Earth	*Sun*
Iron	Magnesium
Magnesium	Sodium
Aluminum	Iron
Nickel	Potassium
Calcium	Calcium
Sodium	Aluminum
Potassium	
....	....
Titanium	Manganese
Chromium	Nickel
Manganese	Chromium
Cobalt	Cobalt
	Titanium
....	....
Copper	Vanadium
Vanadium	Copper
Zinc	Zinc

Not only are the most abundant metals the same in the two cases, but also those which are relatively abundant in comparison with their neighbors of similar

atomic number—iron, nickel, strontium, and barium. The unusually rare elements are also identical,—lithium, beryllium, scandium, gallium and indium. It is hard, indeed, to find a single case in which we can be sure that a given metal is more or less abundant in the Sun than on the Earth. The differences between the abundance in the Sun and in our assumed mixture of granite and meteorites are undoubtedly much less than those between the last two.

This substantial identity of composition looks like the most convincing evidence of a common origin. But we must not be hasty in our interpretation, for Miss Payne's studies of stellar spectra show an almost equal degree of similarity in composition between the Sun and hundreds of other stars. It may be that they were all originally formed out of the same vast mass; or, alternatively, the relative number of atoms of different kinds may result from some process of atom-building or disintegration, which, whatever it started with, has settled down to about the same final and stable state.

When we turn to the non-metallic elements, we find a strikingly different situation. Taking the metals, which agree so well with one another, as a standard, we find that silicon is about equally abundant in the Earth and the Sun, and probably oxygen and sulphur as well (though it is harder to estimate their amounts). But carbon appears to be between ten and a hundred times as abundant in the Sun as here, and hydrogen even more so. In terrestrial rocks the number of atoms of hydrogen is nearly equal to the average for one of the six rock-forming metals. In the solar atmosphere,

there are some three hundred times as many atoms of hydrogen as of all the metals together. Even a greater discrepancy appears for nitrogen. This can be detected in the Sun only by a few faint lines absorbed by very highly excited atoms. They would not appear at all if nitrogen were not as abundant as the commonest metals. Nitrogen lines are conspicuous in the hotter stars and in nebulæ, and there can be no doubt of its high cosmic abundance. Yet there is practically none of it in the rocks. The amount free in the atmosphere amounts to less than a millionth part of the Earth's mass; and provides less than one nitrogen atom for a hundred thousand atoms of iron. There may be more dissolved in the liquid iron of the core, or combined with it. This is indicated by the presence of a little nitrogen in meteoric iron—about one atom to 30,000 of the metal, according to the Noddacks. Making a liberal allowance for this, we may none the less conclude that nitrogen is ten thousand times more abundant in the Sun than on Earth.

The rarest of all elements on Earth (except the short-lived radio-active products) are the inert gases, as was first pointed out by Aston.

Argon forms 1/108 part, by volume, of the atmosphere, and contributes only one out of 130 millions among all the Earth's atoms, or one for 40,000,000 metallic atoms. Neon, helium, krypton, and xenon are respectively, 1/500, 1/1800, 1/9000 and 1/100,000 as abundant as argon atoms. There is no reason to believe that any of these elements, except helium, are present in the Earth's interior. Helium, however, is being

steadily formed by radio-activity, and the uranium and thorium in the granitic rocks, during the last 1500 million years, must have produced 2000 times more helium than is now present in the atmosphere. The deeper layers contain much less of these elements, so that the whole amount of terrestrial helium is probably a few times greater than that of argon.

Helium is evidently an abundant element in the Sun, but its amount is hard to estimate, since it shows but one very faint absorption line. Unsöld estimates its atomic abundance as 1/100 that of hydrogen, which is three times that of all the metals together. Its terrestrial abundance can hardly be as great as one ten-millionth of this.

No neon lines, bright or dark, have yet been found in the spectrum of any part of the Sun; but they appear in the hotter stars and in the nebulæ with sufficient strength to indicate that neon is not a rare element cosmically. The number of its atoms may be of the order of 1/100 that of all the metals together, which is 500 million times as great in proportion as on Earth.

Argon lines have also been detected in a few cases. They are as favorably placed, on the whole, as the neon lines, and it is probable that argon is no more abundant, cosmically, than neon. On Earth it is concentrated at least a thousand-fold, relatively to the latter.

Another example of concentration is furnished by the two isotopes of hydrogen. Here on Earth one hydrogen atom in five thousand is of the heavy kind

—deuterium. The lines of this substance, though close to the ordinary hydrogen lines, are far enough away to be easily separated with a good spectroscope. They do not appear in the solar spectrum, nor in that of the chromosphere during a total eclipse, when they should be seen on a dark background under favorable conditions. From this fact, Menzel concludes that the abundance of deuterium in the Sun is less than 1/500,000 that of the lighter isotope.

These facts may be summarized in one sentence: *The Earth, compared with the Sun, is very poor in the atmosphere-forming elements.* Put thus, they suggest their own explanation—that an immense amount of atmospheric gases has escaped from the Earth.

In confirmation of this, we may note that a similar analysis, applied to the Moon, would find no atmosphere at all; on Mars, it would find very little; and on Saturn a very great deal, including large quantities of free hydrogen or helium—the extent of the atmosphere increasing with the difficulty of escape. But there are serious quantitative difficulties. Jeans' formulæ, which are based on unchallenged principles of the kinetic theory of gases, indicate that the Earth should not at present be losing anything, even hydrogen; and this conclusion still holds, even if we assume that the temperature of the uppermost layers of the atmosphere is 100° Centigrade (as indeed it may actually be, owing to the absorption of the Sun's ultra-violet radiation by ozone). Helium should be still safer against escape; yet there is conclusive evidence that the Earth is actually losing it. During the decomposi-

tion by weathering of the masses of igneous rock which have gone to form the sediments of all the geologic ages, most of the helium previously produced in them by radio-activity would escape into the air. The amount of this helium (by the data of page 56) comes out 45 times as much [1] as is now in the atmosphere. No reasonable adjustment can remove this discrepancy, and there appears to be no escape from the conclusion that a slow loss of helium actually happens.

The speed required for the escape of an atom—11.2 km/sec—is too high to be communicated by any reasonable, even if very improbable, process of thermal excitation. But another possibility exists. The green auroral line is always present in the spectrum of the sky at night, that is, the upper air is faintly self-luminous. This particular line is emitted only by an oxygen atom which by one form or another of excitation has got into a definite metastable state. In such a state, the atom, though still loaded with energy, has but a slight tendency to unload itself and emit light. Instead of doing so in a hundred-millionth part of a second, as most excited atoms do, it may take a whole second, or even longer,—the average interval depending on the particular transition which occurs. This is a very long time indeed from the atomic standpoint, and, except in an exceedingly rarified gas, it is highly probable that some other atom or molecule may collide with it first. It is then possible for the atom to unload its store of energy by setting itself and its neighbor

[1] Allowing for the fact that the *average* age of these rocks, at the time they were weathered, must have been about half the present age of those that are left.

into violent motion. A metastable oxygen atom, colliding with one of helium, could thus impart to it a velocity of 12.6 km/sec—recoiling itself at a quarter of this speed, since it is heavier. Oxygen atoms in this state are certainly present in the upper atmosphere, and some helium atoms must collide with them and be speeded up. Every such atom will escape into space, unless it hits another atom on the way and bounds back. This will usually happen, but the loss, though small, will be steady. Any individual helium atom will fly about in the atmosphere a long time before it escapes; our rough data indicate that it will remain, on the average, for about thirty million years before it gets away.

Hydrogen atoms and molecules would be set going even faster by such collisions; and there is actually no evidence, chemical or spectroscopic, of free hydrogen in the atmosphere. Heavier atoms, such as oxygen or neon, would not be set going fast enough to escape. The energy to load up the oxygen atoms comes from absorption of sunlight—probably very short ultra-violet waves, which break up the molecules into atoms and load energy into them too. The ozone which is so bitter an enemy to the spectroscopist is a by-product of the reaction.

Free oxygen in the atmosphere is essential for the whole process, so it may be that the vegetable life of the Earth results indirectly in the banishment of helium from the atmosphere.

The depletion of neon and nitrogen cannot be explained in this way, and all the evidence indicates that

no loss of these gases has occurred since the Earth was at its present temperature, or anywhere near this.

To lose the greater part of its neon, a body of the Earth's size and mass would have to maintain a surface temperature of 5000° K for millions of years, or 8000° for a few centuries. No process known to science could have kept so small a body so hot for anything like so long. The difficulty is resolved by assuming that the primitive Earth was very much hotter, but for only a short time. In such a case, the rates of escape would have been much faster, but less glaringly unequal for the lighter and heavier gases. Had the high temperature lasted, the Earth would have lost every trace of atmosphere; but a rapid cooling would stop the escape, leaving neon more depleted than argon.

This hypothesis accounts for the main facts. It compels the belief, however, that most of the Earth's oxygen, as well as the nitrogen, was lost, and all the original helium and free hydrogen. Water vapor, being lighter than neon, would go too, even if the temperature was low enough for this compound to exist during the time when most of the escape took place.

It is of interest, in this connection, to note that those gases or vapors which can be absorbed by molten lava, such as water and carbon dioxide, especially under pressure, are or probably have been abundant on the Earth, and are still emitted in great quantities by volcanoes. Trapping of these substances in the molten magma may account for their preservation, as has often been suggested.

The greatest difficulty is the high differential con-

centration of deuterium. Atomic or molecular hydrogen, whether light, or heavy, would escape faster and more completely than anything else, while the difference in the molecular weights of the hydrogen compounds seems hardly to be a great enough fraction of the whole to account for the highly selective result. But, since we know nothing as yet of the relative absorbing powers of molten lava for light and heavy water, no decisive answer is possible.

In fine, then, it appears that, if a mass of material, similar in composition to the Sun's surface, and containing enough heavy elements to make the Earth, could have been removed when very hot and allowed to cool rapidly, a body very similar in composition to our planet would have resulted—though the greater part of the original mass (mostly hydrogen) would have escaped during the process.

If it might safely be assumed that absolutely no neon entered into the composition of the Earth's rocks, or its core, another important inference might be drawn; namely, that part at least of the Earth's mass had, throughout its history, been collected in a body much larger than the Moon, and probably at least as large as Mars. But the atmospheric neon composes only 1.0×10^{-11} of the Earth's whole mass and very careful investigation would be required to detect so small an amount in rocks or meteorites.

One circumstance, not previously mentioned, suggests that the materials whose analyses we have been discussing have, at some time or other, been exceedingly hot. The light elements, in general, are very

abundant; but there are three extraordinary exceptions. Lithium and beryllium, both on the Earth and Sun, are only about 1/100,000 as abundant, and boron, which comes next in order, perhaps a thousandth part as plentiful as might be expected by interpolation between hydrogen and helium, on one side, and carbon, nitrogen and oxygen, on the other.

None of these elements is radio-active, and there can be no thought of their having disintegrated into lighter ones. But the theoretical predictions of Atkinson, confirmed by the brilliant discoveries of Cockroft and Walton, and of many later investigators, show that the nuclei of these light atoms, though stable when left alone, are subject to disturbances when hit by a fast-moving nucleus of helium or hydrogen. In some cases the atom is built up into a heavier one, with emission of a proton or neutron; in others it breaks apart into alpha-particles, and so ends up as helium: but, in either event, these nuclei are more liable to be damaged by hard knocks than are the heavier ones. In a very hot gas, therefore, where occasional atomic collisions of great violence occurred, we should expect atoms of these elements to be built up or broken down, till very few were left.

This explanation of their rarity is generally accepted, but the temperatures required to produce such an effect are very high. An electron or proton accelerated by a potential of only one volt has as much energy as the average atom in a gas at a temperature of 7600° K. The disintegrations in the laboratory appear only when voltages ranging from tens of thousands up to

millions are employed. Making due allowance for the fact that, in a hot gas, occasional collisions will have ten, and a very few even twenty times the average violence, it appears, nevertheless, that impacts hard enough to disturb the nuclei will occur, from thermal agitation alone, only at temperatures of millions of degrees at the least.

It is only deep in the interiors of the stars, therefore, that such atomic transmutations can happen. How much interchange of material there is between these regions and the surface, we do not know. If only the slow processes of gaseous diffusion are at work, the depletion of the lighter atoms from the surface would be so slow that little effect would be produced in a billion years; but if there are internal currents, the mixing may be fairly complete.

Once more, however, we must be cautious. The observed rarity of the light elements is very much what would result in a mixture which once contained them in abundance, if it should be kept at a temperature of millions of degrees. But we cannot prove that these elements were ever more abundant than they are now since we know nothing about their ultimate origin, or that of anything else.

We may, however, investigate the planets and see whether they, too, show signs of ever having been hot.

Small bodies, like asteroids, would lose all atmosphere, and can tell us nothing. The Moon could barely hold carbon dioxide at her present noonday temperature, but would lose it, and all other plausible atmospheric gases, if only a little hotter.

For the larger planets, we have again the great aid

of the spectroscope. Only the atmospheres are accessible to analysis, but a good deal has been learned.

Even a cold gas absorbs its ultimate spectral lines (or bands, if it is composed of molecules). For many gases—hydrogen, nitrogen, helium, etc.—these are in the far ultra-violet, and we cannot detect them. But some of the most interesting exert absorption in the accessible region. These bands are mainly in the less refrangible region—from the yellow to the infra-red—and, though absorbed by molecules in their normal state, they are absorbed but feebly, so that a large quantity of gas is required to produce them.

The bands of oxygen and water-vapor appear in the solar spectrum, but are absorbed exclusively in our atmosphere, and not at all in the Sun's—which is too hot to permit the existence of these particular molecules, and too thin to produce perceptible absorption even if they were there. The great oxygen bands in the red—Fraunhofer's A and B—contain strong lines, but these, though produced by the equivalent of a mile and a half of oxygen at ordinary pressure, are no stronger than the sodium lines absorbed by half an inch of dilute vapor.

To the astronomer seeking to study the atmosphere of another planet, they are a nuisance, for unless there is more oxygen or water-vapor in the planet's atmosphere than in ours, the strong local absorption conceals what we are looking for. An ingenious way of escape, invented independently by three distinguished American astronomers,[1] is to photograph the spectrum of the planet when its distance from the Earth is changing

[1] Lowell, Campbell, and St. John.

rapidly. This motion displaces all its spectral lines a little, while those produced in the Earth's atmosphere are of course unaltered. The maximum shift is hardly enough to get the planetary lines clear of the others; but, even so, a faint planetary line on one wing of the stronger one would make it appear unsymmetrical. The microphotometer, which shows just how the intensity varies from point to point across the width of a line, should reveal even a small asymmetry.

Yet when this powerful method was applied with the great instruments at Mt. Wilson, the results were negative. Excellent spectrograms, of Venus and of Mars, show the telluric oxygen lines alone, with no displacement or even lack of symmetry, such as might be attributed to faint lines of planetary origin. Adams and Dunham conclude from this that the amount of oxygen above a square mile of Mars' surface can hardly exceed a thousandth part of that on Earth, while for Venus substantially the same is true. The spectroscopic test for water-vapor is less delicate, but the absence of perceptible effect indicates that both planets' atmospheres—and surfaces—must be extremely dry.

The spectrum of Venus, however, exhibits three well-defined bands in the deep red, which have been identified as due to carbon dioxide. They are feebly absorbed, and it takes a path of 40 meters through the gas at 10 times atmospheric pressure to produce them very faintly in the laboratory. They are much stronger in the planet, indicating that the amount of carbon dioxide above Venus' visible surface is equivalent to

at least a mile of the gas at standard pressure. As the visible surface is composed of clouds or haze, the total quantity may be much greater. Schönberg, studying the diffuse reflection of light, concludes that it amounts to about as much as the Earth's whole atmosphere.

The Sun's rays penetrate this freely to the cloud-level, and filter down to the actual surface, while absorption by the gas greatly hampers the escape of the outgoing long-wave radiation. The planet's surface should therefore be hot—Schönberg estimates its temperature as near the boiling point of water. The absence of any notable quantity of water-vapor in the atmosphere indicates that there can be no oceans on the planet, and probably no free water at all. Wildt suggests that it may all have been taken up in hydrated minerals,—but this would be barely possible if there had been anything like as much as there is in our oceans, and the great difference is really surprising.

A waterless planet can hardly be the abode of life, such as we know, and the absence of oxygen and the great abundance of carbon dioxide confirm this belief. Venus, except for the absence of water, may well represent a very ancient condition on Earth, before life began.

Mars has a thin atmosphere, probably not enough to show the bands of carbon dioxide, even if this formed a considerable fraction of it. The total quantity of water in the polar caps must be small,—for they disappear completely in a summer cooler than our spring, while the Earth retains huge areas of perma-

nent ice. The maximum amount which could be evaporated by the Sun's heat can easily be calculated. They cannot be more than a foot or two thick, and the whole quantity of water in them would not fill Lake Erie. Dispersed in the atmosphere, it would be so attenuated that the failure to detect it spectroscopically is not surprising.

There is no direct evidence of oxygen, but there is strong indirect evidence in the red color of the planet, which is just what would be shown by a surface stained by ferric oxide. On atmosphereless bodies like the Moon, there is not a trace of red,—the grays and at most the dull browns of unweathered rocks prevail. It is tempting, and indeed most reasonable, to think that in Mars we see what the Earth may some day become —a planet in which the weathering and oxidation of rock have gradually robbed the atmosphere of practically all its free oxygen. Wildt makes the interesting suggestion that, with so little oxygen, the lower layers would resemble the upper parts of the Earth's atmosphere and contain ozone. This is a very powerful oxidizing agent, and may have accelerated the locking up of the oxygen in the surface materials.

The past existence of free oxygen strongly suggests the former presence of vegetable life on Mars. The seasonal changes of the dark areas have long been interpreted as vegetative, and there would appear to be no sufficient reason for rejecting this interpretation, even though the atmosphere is now almost devoid of free oxygen. If there was enough there in the past to keep life going, the exhaustion by weathering would be ex-

ceedingly slow, and the evolution of life may well have kept pace with it—plants developing means for utilizing for their own internal respiration the oxygen produced by photosynthesis, just as desert plants on Earth have "learned" to store up water and protect themselves from evaporation.

If intelligent animal life ever existed on the planet (concerning which we have no decisive evidence) even it may have survived the change. At least, the human race, at its present level of intelligence, would be able to secure its survival, though in diminished numbers, in enclosures supplied artificially with oxygen;—provided it had the millions of years of warning that the change would undoubtedly give, and provided that it took the trouble!

There is, of course, not the slightest reason to fear such a catastrophe on Earth. At the present rate of rock weathering, there is enough oxygen in the atmosphere to last for a billion years.

The spectra of the major planets are again different. Strong bands in the orange and red were discovered in Jupiter's spectrum in the early days of spectroscopy. Saturn shows the same bands—stronger for the most part—in the spectrum of the light reflected from the ball of the planet, but none at all in that from the ring—which is, of course, quite devoid of atmosphere. Under moderate dispersion—as with prism spectrographs—these bands appear diffuse; but with high dispersion they are resolved into a multitude of fine lines.

They are still stronger in Uranus, and enormous in

the spectrum of Neptune, where they cut out so much of the red and yellow light that these planets appear conspicuously green, despite some absorption in the green and blue.

Till very recently, these bands were unidentified—one of the last unsolved problems of spectroscopy. But, Wildt, a few years ago, discovered that some of them agreed with known absorption by ammonia gas, while others were produced by methane. This identification has been settled beyond all doubt by the high dispersion spectrograms obtained by Dunham. More than sixty absorption lines produced in a long tube filled with ammonia gas agree exactly, in position and intensity, with the components of bands in Jupiter's spectrum, while eighteen lines of methane have been identified in a band in the infra-red. Within the last few months Slipher and Adel have shown that practically all the outstanding bands are due to methane. To produce the great bands found in Neptune would require a layer of this gas thicker than the Earth's whole atmosphere.

The methane lines are stronger in Saturn than in Jupiter, while the reverse is the case for ammonia. The latter observation is readily explained as an effect of temperature. Saturn gets less heat from the Sun than Jupiter; its atmosphere is colder, and almost all the ammonia is frozen out of it.

From the strength of the ammonia lines, Dunham estimates that the amount of the gas above the planet's cloudy surface is equivalent to a layer about thirty feet thick at standard temperature and pressure. Such a

layer of gas would produce, by its own weight under Jupiter's attraction, a pressure of about 1/500 of a "standard atmosphere." Now the vapor pressure of ammonia has this value at a temperature of —107° Centigrade. If the planet's atmosphere were colder than this, it could not contain as much ammonia as it does. In an atmosphere composed mainly of hydrogen, the light molecules would, so to speak, carry a part of the weight of the heavier ones of ammonia, the pressure of ammonia would be less, and the limiting temperature would be close to —120° C.

The clouds which form Jupiter's visible surface may therefore consist largely of droplets of condensed ammonia.

A rotating black body, warmed only by the Sun, would have an average surface temperature of —150° C. at Jupiter's distance, and —180° at Saturn's. The ammonia bands show that the actual temperatures are considerably higher. This may be explained by the presence of a residue of internal heat in the planet, or by heavy absorption of long waves in the atmosphere, which prevents the heat which sunlight carries to the cloud-surface from getting out again easily. The Earth's temperature is raised about 15° Centigrade by this effect; how great it might be on Jupiter has not yet been calculated.

The theoretical temperatures for Uranus and Neptune are —210° and —222°. This would condense methane, nitrogen, oxygen, and everything else but hydrogen, helium, and neon,—which most certainly would not show any absorption bands in the visible

spectrum. The heavy methane bands show that the actual temperature is a good deal higher.

We may note that the differences in composition between Jupiter and Saturn and the terrestrial planets are just what might be expected on account of their greater masses. The escape velocity from Saturn is 36 kilometers per second. It would retain all gases, even hydrogen, unless its surface were kept at 5000° for millions of years. For Jupiter the velocity is 60 km/sec and the temperature 14,000°.

Masses of this magnitude, if originally similar to the Sun in composition, would retain most, if not all, of the lighter constituents. When they cooled down, they would be surrounded by enormous atmospheres, composed mainly of hydrogen, with smaller amounts of helium and of the compounds of hydrogen with the other abundant elements,—that is, methane, ammonia, and water. The latter would freeze out at the low temperature, and the resulting atmosphere would be strikingly like that which is observed. Ammonia should be thoroughly frozen out of the atmospheres of Uranus and Neptune. The absence of the ammonia clouds, permitting us to see deeper, may explain why the methane bands are so strong.

In this case we can be quite sure that the planets have not been formed wholly by accretion of small bodies, for these would have lost the hydrogen and other light gases. There must have been a massive nucleus from the very beginning. This interpretation of the low densities of the major planets was first given by Moulton.

Comets show beautiful and characteristic spectra. Superposed on a continuous spectrum—showing the Fraunhofer lines and due largely and perhaps entirely to reflected sunlight—are bright bands, which have been definitely identified as due to compounds of carbon. The strongest of these arise from the carbon molecule, C_2, those in the violet are the bands of cyanogen, *CN*, and hydrocarbon, *CH*. These are characteristic of the heads; the tails give quite a different spectrum, including bands of ionized molecules of nitrogen and carbon monoxide. The energy which sets all these shining is derived from, and continuously replenished by, the Sun's light. For our present purpose, the important points are that the elements which compose the cometary gases are the same which are so abundant elsewhere, and that gases of very low boiling point, such as carbon monoxide and nitrogen, can survive for ages within the meteoric bodies which doubtless constitute the main part of a comet's mass, only to emerge in often-renewed supplies when these bodies become heated at perihelion. Comets close to the Sun usually show bright lines of sodium, both in head and tail. This is intelligible in principle; but why they sometimes appear when a comet is forty or fifty million miles from the Sun, and not nearly hot enough to evaporate ordinary sodium compounds, is hard to explain. There are plenty of other puzzles. The band spectra in the head come from chemically unsaturated molecules,—broken fragments of the familiar ones, which we may suppose to have existed in the meteoric masses. How these molecules become dissociated we

do not know. To remove an electron from the very stable molecules of nitrogen and carbon monoxide requires still more energy, and it is not clear how this happens.

But we have, fortunately, no need to pursue this difficult inquiry for our present purpose. We may be content with the conclusion that the properties and chemical composition of the smaller bodies of our system are strikingly similar to those which might be expected of masses, large and small, which had been removed from an intensely heated source similar in composition to the outer parts of the Sun, and allowed to cool rapidly.

III

THEORIES OF ITS ORIGIN

THE solar system is most evidently not a product of chance. The common direction of orbital motion for every one of the 1300 known planets is alone sufficient to settle this; and the small eccentricities and inclinations of the larger planets add proof upon proof. These conspicuous regularities offer too open a challenge to be ignored; and suggestions for their explanation have been made at intervals for centuries.

The oldest hypothesis which now deserves mention was first suggested by a theologian, Swedenborg, and a philosopher, Kant, and was later put into scientific terms by Laplace,—who, however, contented himself with a general, semi-popular statement, and never published any detailed quantitative discussion.

According to this view, the matter which now composes our system was once widely dispersed in the form of a huge, diffuse, slowly rotating nebula, which was gradually cooling and condensing. As it contracted, its period of rotation necessarily diminished, by the conservation of angular momentum, and the centrifugal force at its equator increased, and ultimately became equal to the acceleration of gravity. At this time, or

perhaps a little before, a ring of matter split off round the equator, leaving the main mass to contract further.

The material of this ring, in some way not exactly specified, condensed to form a planet. Successive rings, abandoned at wide intervals, thus formed the planets of our system, and at last the residue gathered itself into the Sun.

Planets thus produced would all move in the same direction—that of the original rotation—and have nearly circular orbits, almost in the same plane; so that the obvious features of the system are accounted for. The asteroids, discovered since Laplace proposed the theory, are accounted for as fragments of a disrupted ring. The forward rotations of the planets can be explained if the outer parts of the original ring were moving faster than the inner, and, if a ring itself contracted into a smaller nebula before it condensed into a planet, it might give birth to a satellite system.

At first sight this theory is very attractive, but it meets with fatal dynamical difficulties. First, historically and logically, is the fact that a ring of the supposed type would not and could not pull itself together lengthwise and coalesce into a single body. Maxwell's dynamical analysis (1859) showed that if originally fluid, it would tend to break up into a multitude of small parts (much as a thin stream of falling water breaks into drops). These would combine into larger ones; but this tendency to coalesce would not last long, and the final, stable state would consist of a large number of small bodies pursuing very similar orbits. It might form a swarm of asteroids, but not a

single planet. That such a swarm of particles is actually stable is proved by the permanence of Saturn's rings.

This objection disposes of the original Laplacian form of the hypothesis. It is imaginable, however, that the planets may have begun to form as condensations inside the nebula, while its surface extended far beyond their orbits. But here we run into a fundamental and still more fatal difficulty—the distribution of angular momentum in the system. The major planets, which have less than 1/700 of the whole mass, carry 98 per cent of the angular momentum; the Sun, with practically all the mass, only two per cent. The puzzle is why the Sun has so little, not why the planets have so much—for any bodies revolving in orbits of the same cross-diameter must necessarily have as much angular momentum per ton as the planets do, so long as the central mass is as great as the Sun's. Whether this mass is expanded into a nebula extending almost to the planet's orbit, or concentrated into a star, makes no difference at all.

But if all the mass and angular momentum of our system could be collected in the Sun, it would then rotate in about twelve hours, and be less flattened at the poles than Jupiter. The centrifugal force at its equator would be about five per cent of gravity, and it would be far from any danger of breaking up. The importance of angular momentum was stressed by Babinet in 1861, but the extraordinary character of its actual distribution was first pointed out by Fouché in 1884, and re-emphasized by Moulton in 1900.

No one has ever suggested a way in which almost the whole of the angular momentum could have got into so insignificant a fraction of the mass of an isolated system. We need not go here into the mathematical methods by which Moulton, Jeans, and others have shown that one or another proposed scheme is impossible. The observed situation is not at all the kind of thing that could result from the gradual and cumulative action of internal forces. For once the uniformitarian school of interpretation fails, and we are driven to catastrophism,—to the belief that the planets were separated from the Sun and their angular momentum put into them by the action of some external and transitory force. The three principal theories which merit discussion all attribute the genesis of the planets to a *close encounter* between the Sun and another star, which in their wanderings through space passed very close to each other.

In the planetesimal theory of Chamberlin and Moulton, and the tidal theory of Jeans and Jeffreys, it is supposed that the two bodies narrowly missed each other; in Jeffreys' later theory that an actual "side-swiping" collision took place. The star—or what was left of it, on the third hypothesis—passed on in a hyperbolic orbit and disappeared; but the catastrophe caused the ejection of great quantities of matter. Much of this fell back into the Sun; some may have followed the star, or escaped independently into space; the rest, impelled laterally by the star's attraction, (or by the shock of collision, if this occurred) formed the raw material of the planets.

These hypotheses, which have much in common, possess great advantages. The angular momentum of the planets is now attributed to an external source, and supposed to have been acquired at the expense of a small fraction of the enormously greater amount possessed by the passing star. The ejected material, after the encounter, would obviously be moving almost in the plane of the star's orbit around the Sun, and in the same sense. The comets, which were practically unexplained on the Laplacian hypothesis, may perhaps be accounted for as scattered débris of the great wreck. These hypotheses are also liable to grave objections; but before considering these we may take up the various theories in detail.

The first two may well be discussed together, for, although they differ in important details, they have still more in common.

It is agreed by all investigators, that, unless the passing star had come within a few diameters of the Sun, nothing much would have happened. The tidal force due to the star's attraction would distort the Sun a little, and vice versa. As the bodies receded after periastron passage, the tides thus raised would settle back, and the Sun might be left oscillating in form,—now elongated and now flattened,—and become perhaps a slightly variable star until the pulsation died down from friction. But if the star came very close, so that its attraction on the nearest part of the Sun's surface was much stronger than upon its center, and counteracted a considerable fraction of solar gravity, emission of material might occur.

Chamberlin attributes this ejection to the combination of upward tidal attraction, expansion of the hot compressed solar gases, as the load above them was decreased, and a "propulsatory force" such as is exhibited in the motion of solar prominences. He assumes that a succession of huge eruptive "bolts" were ejected to great distances, even beyond the orbit of the star, and pulled sidewise by its attraction, so that, after this had receded, they were left traveling in orbits of moderate eccentricity and became the precursors of the major planets. Meanwhile, from the opposite side of the Sun, where the tidal forces were much smaller, a set of weaker eruptions sent out smaller bolts, which ultimately became the terrestrial planets.

Jeans and Jeffreys base their reasoning on the changes in form which the Sun as a whole would undergo by the action of the tidal forces. As the star approached, the Sun's surface would rise toward it, and finally become pointed,—after which a stream of matter would flow out toward the star, forming an elongated filament. Such a configuration is longitudinally unstable, and would break up, under its own gravitation, into a string of separate masses,—which, attracted laterally by the star all through this process, would be left, when it receded, moving in elliptical orbits about the Sun. The outflow would be greatest when the star was nearest, and the filament thickest near its middle, so that the largest planets should be found near the middle of the range of distance. On the far side of the Sun, the forces would not be sufficient to cause an outflow.

The two theories agree that, as soon as the ejected masses were clear of the Sun, they would begin to cool rapidly, and that the more refractory constituents would liquefy, leaving quantities of uncondensible gas; but at this point they diverge.

Chamberlin and Moulton maintain that the condensation would form innumerable separate small bodies, or planetesimals, which would quickly solidify. Many of these,—apparently the majority,—escaped to pursue individual orbits around the Sun. The rest formed swarms—the remnants of the original bolts—which collected into solid cores—the nuclei of the present planets. The larger nuclei were always massive enough to hold the lighter gases by their attraction. Meanwhile, the innumerable isolated planetesimals would spread out into a flattish disk, of widely scattered small masses, all revolving about the Sun in a common direction. As the cores swept through this disk, they picked up planetesimals, one by one, until they gained greatly in size and mass, and having used up the material available for accretion, became the present planets. The infall of the planetesimals, on the whole, would tend to slow the planet when it was moving fastest, and speed it up when moving slowest, and so to diminish the eccentricity of its orbit—thereby reducing the original eccentricities, which may well have been high, to the present small values.

According to Jeans and Jeffreys, the planets started as masses of very hot gas, by segmentation of the original filament. A large fragment, massive enough to keep the lighter gases from escaping at its surface,

would cool rapidly by radiation—on the outside at least—until the more easily condensed constituents formed drops of liquid (just as raindrops do in the air). These would fall inward, under gravity. At first they might be vaporized again, but, as the cooling continued, they would collect and form a liquid core, with the densest liquid (probably molten iron) at the center, surrounded by a permanent atmosphere.

A mass of gas so small or so hot that it could not retain the lighter gases would expand very rapidly, cooling as it did so both by radiation and on account of the expansion. Liquid drops would form in the outer portions. Many of them might be carried away into space by the flow of the expanding gas; but others might fall in, and would produce a liquid core much like the other, but smaller, and with little or no atmosphere. The escaping drops of metal or lava, and any which might have condensed from other parts of the filament, would quickly solidify into planetesimals, exactly like those of the other theory, and these would be accompanied, on both theories, by large amounts of gas. Neither planetesimals nor gas would be able to get away from the Sun's attraction—barring perhaps some which were set in very rapid motion by the initial catastrophe—and they would spread out into a discoidal mass, revolving about the Sun. As the planets moved through this resisting medium, their motions toward the Sun or away from it would be slowed down by friction, diminishing the orbital eccentricity. The forward motion of the planet would be little affected, as the particles or molecules of the medium would be moving forward, too.

The two hypotheses, though differing in important particulars, are really very similar in general outline. The general history of our system is much the same on both. A defect of the planetesimal theory in its original form was its assumption of enormous and undefined propulsional forces, which helped to eject the bolts from the Sun. A generation ago, when the theory was first proposed, the nature of the forces which repelled eruptive prominences and comets' tails from the Sun was almost unknown, and it was permissible to speculate that it might be able to lift great masses. But it is now practically certain that the active influence is radiation pressure, which can impart very high velocities, but only to extremely small particles, and is quite incompetent to repel so much as a grain of sand. Indeed, the whole vast flood of the Sun's radiation could only hold up, against its gravitational attraction, material enough to form one small asteroid ten miles in diameter.

The assumption that the expulsion of matter from the Sun would take place by a succession of paroxysmal outbursts appears also to be doubtful.

This leaves tidal force, aided by the pressure of the hot solar gases, as the only available ejecting agent. The distortion of the Sun, up to the beginning of ejection, can be calculated by a fairly good approximate theory—which, however, takes little or no account of the expansive force of the heated gas—but the formation and motion of the filament are far too complicated for exact calculation. The segregation of the gaseous filament into separate masses can again be handled by theory, but only in a very generalized way, and the

same is true of the subsequent cooling and condensation.

It is here that the two theories part company,—the planetesimal supposing that the existing planets were formed mainly by the slow agglomeration of small cold bodies, and the tidal that they were all once liquid and have picked up much less matter in later times. This difference, while very important to the geologist, is really rather small from the standpoint of the astronomer.

It is regrettable that a few enthusiastic supporters of the older form of the theory have at times emphasized the differences between it and the newer, rather than the essential similarities. Should the modifications made a few years later turn out to be improvements, there is danger that the older formulation may be regarded by the inexperienced as discredited, rather than amplified, and that the brilliant originality of the earlier investigators may fail of adequate appreciation —though it has been expressly recognized by the later workers. They, too, deserve full credit—"there is glory enough to go round."

Both theories conclude that the planets' orbits were once much more eccentric, but have been "rounded up" as a result of motion through a medium, composed, for one, of planetesimals and gas, for the other, of gas and planetesimals. The total mass of this material may well have exceeded that of the primitive planets,—indeed, the planetesimal theory explicitly asserts this. Jeffreys has shown that, under these circumstances, the aggregate cross section of the planetesimals must have

been vastly greater than that of the planets, so that any given planetesimal was practically certain to make many collisions with others before it was picked up by a planet. These collisions would smash them into ever smaller fragments—indeed, the more violent among them would volatilize some of the material. The medium would thus resolve itself mainly into a mixture of gas and fine dust, with occasional larger particles surviving.

Very fine dust would be blown away into space by the Sun's radiation pressure; but it may well be that, before all the stuff had been reduced to this size, the differences of motion would have been so "ironed out" by the collisions that the whole assemblage would move practically in circles around the Sun, each part with the velocity a planet would have at the same distance. Such a medium would be effective in reducing the eccentricity of an orbit, but, on the average, would neither take up much angular momentum from the planets nor impart much to them.

Difficulties arise, however, in explaining the rotation of the planets, and the orbits of their satellites.

The principal expounders of the planetesimal theory disagree regarding the initial rotation of the masses ejected from the Sun, Moulton believing that it may have been in any direction, and Chamberlin that it was about axes lying in the planes of the orbits. This difference is however unimportant, for both agree that the present direct rotations arose mainly from the effects of the infall of planetesimals. Moulton concludes that, under certain circumstances, this rotation

would have been direct and rapid; but his postulates have been criticized by H. F. Reid, who concludes that the rotation would be slow. Indeed, as Nölke remarks, if the planetesimals were all moving in exactly circular orbits, those which fell on the outer hemisphere of the planet farthest from the Sun, would be moving slower than those which hit the inner hemisphere, and the resulting rotation would be retrograde.

The satellites, on this hypothesis, are believed to have arisen as small secondary nuclei, ejected from the Sun close to those of the planets, and with such velocities that they remained revolving around them—while others may have escaped to become asteroids. As planetesimals fell into the growing planet, others hit the satellites. Moulton concludes that this would gradually enlarge the orbit of a direct satellite, and make it more nearly circular, while a retrograde satellite, or one with a highly inclined orbit, would be forced nearer and nearer the planet till it fell into it; but his arguments do not explain why all the nearer satellites move practically in the plane of the planet's equator, no matter what the inclination of this may be to the orbit.

On the tidal theory, the initial rotation of the planets must have been slow, since the tidal forces acting on the filament could set it in bodily motion, but impart very little rotation, if any. The satellites are supposed to have originated by tidal disruption of the inchoate planet by the Sun's attraction at its first perihelion passage. Most satellites, however, are so small that they could never have held together if they were

gaseous, but must have been liquid or solid from the start. If they were formed tidally from their primaries, the latter must at the time have been liquid, and fairly dense. Jeans has shown that such a mass could not be broken up tidally unless it almost grazed the Sun, and might then produce one or two large satellites, but not a set of small ones.

The changes in the satellites' orbits, while the planet was ploughing through a resisting medium, have never been worked out in detail; indeed, the distribution of the medium itself, in the vicinity of a planet, under the combined attractions of the planet and the Sun, raises very difficult theoretical problems, and has never been adequately calculated. If the planet was surrounded by a *local* resisting medium, rotating about it, condensed toward its equatorial plane, and moving through space with it, a satellite moving within this medium would gradually come into an orbit of small eccentricity and inclination to the equatorial plane. The masses of the satellites are small, and their orbital velocities comparable with those of the major planets, so that the action of the medium should be much faster on them than on the planets, which agrees with the fact that their eccentricities average much less than those of their primaries. It is very hard to see, however, how a planet which carried such a medium revolving about it could itself be affected by the action of a more widely dispersed medium circulating about the Sun.

On the tidal theory, the rotation of a planet is attributed mainly to the falling back of matter expelled

from it, but not set into rapid enough lateral motion to form satellites. Jeffreys calculates that, to produce the Sun's observed rotation, a mass equal to Jupiter's would have to fall back into it—which is plausible. But to account for Jupiter's rotation, the mass reabsorbed by it would have to be 1/15 that of the planet, or 400 times that of all its satellites—which seems absurd.

To meet this difficulty, he revived in 1929 the old notion that the Sun and star actually collided during the encounter. This was suggested as long ago as 1750 by Buffon (who called the other body a comet, but supposed it to be of great mass) and was discussed in considerable detail by Bickerton, of New Zealand, in 1880 and afterwards. There is obviously nothing impossible about such a collision—nor would it be much more improbable than the close approach postulated by the other theories. Should one occur, it would be the most stupendous catastrophe which can reasonably be imagined. The two bodies, drawn by their mutual gravitation, would attain a relative velocity of several hundred miles per second. As they approached, they would be distorted tidally, and eruptions would take place before the actual impact. Unless the collision was very nearly central, the heavy cores of the two stars, which are probably much denser than the average, would miss each other and swing around in a sharp curve to recede again into space. The nearer sides of the bodies would intermingle, forming a transitional layer of gas, greatly compressed by the continual crowding in of new material into it as the distance de-

creased to its minimum, intensely heated by compression and friction, and thrown into exceedingly turbulent motion as the main masses on each side slid by at enormous speed. As the stars separated, the compressed gases would begin to expand and cool, but a part of the original material of each, whose velocity had been checked by intermixtures with matter from the other, would lag behind, so that a flattened "ribbon" of exceedingly hot gas would stretch from one to the other, lengthening, by the persistence of its own motion, as they receded. The whole process, for stars like the Sun, would take only about an hour!

This ribbon plays the rôle of the filament of the tidal theory, or the bolts of the planetesimal: It would cool by radiation and expansion; condensed masses would form, and move through a resisting medium derived from the uncondensed gases and loose solidified fragments, and the subsequent history of the orbits would be much like that envisaged by the other theories,—with one important difference. The fluid friction of the motion of the star past the Sun would impart to all parts of the transition layer a rapid whirling motion, equivalent in general to rotation about axes in the plane of the ribbon, and at right angles to that of the star's orbit or the resulting planetary orbits, and in the direct, or forward, sense. Every resulting mass, large or small, would then be endowed with a fairly rapid direct rotation, while the inevitable fall of parts of the ribbon back into the Sun would set it in relatively slow rotation in the same direction.

The thickness and mass of the transition layer can

be roughly calculated, from the properties of viscous and turbulent fluid motion. Jeffreys concludes that for a typical collision of two stars like the Sun, about 1/500 of the total mass would be entrapped in the transition layer, and that this material would acquire angular momentum enough to set it rotating with a period of about 8 hours, if it could be collected into a single globe. These figures are admittedly only rough estimates, but, nevertheless, they are of the right size to fit the actual planets, instead of being vastly greater or smaller.

The collision theory, therefore, appears to be able to account for the character of the planets' orbits about as well as the other two, and to give a better explanation of their rotation. Like the others, it has difficulties with the satellites,—although almost anything may have happened in the period of wild turbulence which included the formation of the ribbon and its segregation into separate bodies.

All these theories, however, have in common certain grave difficulties. The first, suggested by Nölke, relates to the rounding up of the orbits by the resisting medium. The particles of this medium, whatever their size, would affect the motion of a planet largely by actual collision. For planetesimals and dust, these collisions would certainly be inelastic; they would become part of the planet. To reduce the eccentricity, and the inward or outward motion of a planet to half its original value, by this process, would demand an accretion sufficient to double its mass. A gaseous medium, however, might slow down the motion, even if

much less massive than the planet. Jeffreys illustrates this by the example of a pendulum swinging in a tight case, subject to friction from the air, "which has its oscillations damped out, even though the enclosed air has a smaller mass than the pendulum." This is perfectly true: but the reason why it happens is that the collisions of the air-molecules with the pendulum are *elastic*—they bounce off, and are used over and over again. The same thing would happen to a planet, provided that it was too small to retain an atmosphere; but a planet which possessed one would be a perfect trap for anything that hit it. The major planets have enormous atmospheres, and might, for all we can say, have picked much of them up in this way. But the Earth, though capable of retaining all gases, even hydrogen, has an atmosphere of less than a millionth of its own mass. A gaseous medium formed by ejection from the Sun would be largely composed of hydrogen; yet all the hydrogen in the ocean has but 1/38,000 of the Earth's mass. It appears therefore as if the Earth, since it cooled down and developed an atmosphere, can have accumulated less than a ten-thousandth part of its mass from the hypothetical medium,—which is not enough to affect its orbit perceptibly.

In a medium composed of particles so widely scattered that their mean free path between collisions with one another was large compared with the planet's diameter, an additional resistance would be produced by the action of those which passed close to the planet without hitting it. Such a particle, if originally ahead of the planet, and nearly at rest before the latter ap-

proached it, would swing around it in an almost parabolic orbit, and recede from it almost in the direction from which it had come. It would then be moving around the Sun *faster* than the planet, acquiring the necessary momentum at the expense of the latter.

Particles which did not pass so near would be less deflected, but would be more numerous, and the net effect of them all might be many times greater than that of the much smaller number which actually hit the planet. This influence would be most important for large masses like Jupiter. In a gaseous medium, where the molecules collided at much shorter intervals than it would take them to swing around the planet, it would not happen. In a swarm of meteorites, it might increase the resistance tenfold, or possibly a hundredfold, but, even so, Nölke's objection about the Earth's atmosphere retains its force.

Other, and still more important, difficulties arise if, at the time of the encounter, the Sun was of about the same size as it is at present. That it was so cannot be absolutely established, since no one was there to measure it, but it is strongly indicated both by theory and observation. The Sun's mass, before the catastrophe, must have been substantially the same as at present, and by Eddington's well-established relation, the same is true of its luminosity. Now all known stars of this absolute brightness (and we know a good many) are of nearly the Sun's effective temperature, and doubtless of about the same size.

When the tidal theory was suggested, sixteen years ago, there was little or no objection against assuming

—as its founders then did—that, at the remote epoch when our system originated, the Sun was twenty times as big as it is now, or even much bigger. But advance in knowledge of the stars, and, above all, the realization that the age of our system is small in comparison with the probable rate of stellar evolution, have radically altered our view of the probabilities. Jeffreys, for example, in revising his admirable treatise on "The Earth" accepts the conclusion that the Sun was "in practically its present state"[1] at the time of the encounter.

The first conclusion to be drawn from this is that the matter forming the planets, before ejection from the Sun, must have been under enormous pressure, and very hot.

If this matter could be put back upon the Sun, and spread in a uniform layer over its surface, the pressure at the bottom of this layer would be 1,170,000 atmospheres (as an elementary calculation shows). The corresponding temperature is difficult to calculate, since it depends on the internal constitution of the Sun, but on any reasonable assumptions, it must be more than a million degrees.

Allowance for the ejected matter which did not form planets would raise these figures; allowance for the upper layers, which were cooler and under less pressure, would lower them. Balancing these two factors, there seems no escape from the conclusion that the average temperature of the material, before its ejec-

[1] *The Earth.* 1st Edition, Cambridge, 1924, p. 24; 2nd Edition (1929), p. 25.

tion began, was of the order of a million degrees. If it came from deeper in the Sun, it may have been several times hotter; while, on the collision theory, the temperature of a mass formed by the intermingling of equal parts of solar and stellar material would have been raised to about ten million degrees (depending on the molecular weight) by the kinetic energy of impact, even if it had originally been cold.

At a million degrees, hydrogen atoms have a mean velocity of nearly a hundred miles per second. The attraction of the ejected mass would not begin to be able to hold them back. They would simply diffuse away into the vacuum of interplanetary space, almost as if there was no restraining force. Heavier atoms would go more slowly, but only Jupiter and Saturn could prevent even iron from escaping.

It is hard to see, then, how the ejected material could cool and condense at all. But the rate of radiation from a hot body increases much faster than the pressure, since it is proportional to the fourth power of the temperature instead of the first. At a million degrees, the flood of outgoing radiation (mostly of the nature of soft X-rays) is so intense that it would exert a pressure of 1880 atmospheres—nearly 28,000 pounds per square inch—on an imaginary (and physically impossible) opaque surface which bore its full brunt. An asteroid, 28 miles in diameter, at this temperature, would radiate as much energy as the Sun!

The ejected masses, once they could radiate freely into space, would therefore cool very rapidly. The cooler surface, driven outward by radiation and gas

pressure from the superheated interior, might easily be ruptured, and a new complication added to the confusion. Detailed treatment of such a turmoil is impracticable. There is nothing very surprising about the condensation of small drops, but how bodies as big as the major planets could be formed is not clear.

A much graver difficulty arises when we consider the distribution of angular momentum—not the total amount this time, but the angular momentum per ton. As has already been said, this is proportional to $\sqrt{p}$, the square root of the semi-parameter of the orbit, for all the planets. For the star's motion around the Sun it will be proportional to $\sqrt{p\ (1 + x)}$ where x is the ratio of the star's mass to the Sun's—since the combined attraction of the two increases their orbital velocity at a given distance.

For a parabolic orbit, *p* is twice the perihelion distance; for an elliptic orbit less, for a hyperbolic more. The star had a hyperbolic orbit; but the correction on this account would be but a very few per cent unless its velocity, before being perceptibly increased by the Sun's attraction, was much greater than the average for actual stars.

Now, to produce tidal eruptions, the star must have almost grazed the Sun. If it was of the Sun's size and mass the perihelion distance could not have been much more than a million miles, or no ejection of matter would have taken place. To be liberal, let us call it 1½ per cent of the Earth's distance, or 1,400,000 miles. The parameter *p* is then 0.03 astronomical units; but

the angular momentum per ton should correspond to a distance a little more than double this.

We then have the situation shown in Table V.

TABLE V

Body	*Semi-parameter*	*Angular Momentum per Ton*	*Ratio*
Star	0.03	0.25	1.0
Mercury	0.37	0.61	2.4
Venus	0.72	0.85	3.4
Earth	1.00	1.00	4.0
Mars	1.51	1.24	5.0
Jupiter	5.19	2.28	9.1
Saturn	9.50	3.08	12.3
Uranus	19.11	4.39	17.6
Neptune	30.07	5.49	22.0
Weighted Average		2.63	10.5

The last column contains the relative angular momentum, per ton, taking the star as standard. In the last line we have the average value for all the planets, taking account of their masses. This average angular momentum per ton, for the planetary system, is more than ten times as great as our very favorable suppositions make it for the star.

To put so much angular momentum into the ejected material during the encounter would seem to be impossible. We may get a rough idea of the star's action by supposing that it drags a particle with it, by gravitational attraction, and later releases it to the Sun's unmodified influence—though, of course, both bodies are continually attracting the particle, and only the relative strength of these influences varies.

If the particle, after its "release," is moving faster,

with respect to the Sun, than the star did at the same distance (or even a little slower), it will fly off in a hyperbolic orbit and be lost. Increase in angular momentum per ton, to be useful in planet-making, must come either from altering the direction of the particle's motion to be more nearly perpendicular to that toward the Sun, or from an increase of the particle's distance while it is being dragged along under the star's influence. The necessary increase is alarmingly great. The perihelion distance of a particle moving in an elliptic orbit must always be more than half the semi-parameter. The matter which formed Jupiter, therefore, could not have been fully released until its distance from the Sun was 2.6 astronomical units, or nearly ninety times the distance of the star from the Sun at the height of the outburst,—while Neptune must similarly have been dragged to five hundred times the original distance of the ejected matter which formed it. Even so, the released matter must have been left moving at right angles to the Sun's direction—almost perpendicularly to the motion of the star in this part of its track—and with barely less than the speed of permanent escape. Otherwise we must assume it to have been dragged still further before its release.

It would require laborious and difficult calculations to determine just how great the maximum effect of the star's action could be. But it is evident that this would be attained only under very special circumstances, and that most of the material ejected from the Sun would be dragged to much smaller distances, and left revolving with much less angular momentum. We might ex-

pect, at best, large inner planets and small outer ones —the opposite of the actual arrangement. Indeed, even the inner planets of our system are at or beyond the limit to which it is at all plausible that they could have been dragged.

This argument, incidentally, disposes of all possibility that the satellites could have been formed at a later perihelion passage.

We cannot escape from the difficulty by assuming that the matter dragged to small distances all fell back into the Sun, for it would have brought angular momentum into the latter, and set it rotating faster than it does.

The planetesimal form of the encounter theory meets with exactly the same objection, for it is immaterial to the argument whether Jupiter (for example) was born as a single body or formed by the coalescence of many small ones. The average angular momentum per ton is the same in any case, and if it had been less for some planetesimals, it would have been greater for others.

Something might be gained by the assumption that the planets—or the raw materials to form them—were shot out from the Sun by powerful internal forces. This initial impulse could then be held mainly responsible for getting the planets out to their present distances, while the attraction of the star set them moving sidewise. If it could be assumed that such eruptive forces could be released by the action of a star passing by at a few times the Earth's present distance, the gain would be great. But there are many spectroscopic

binaries, whose components are subjected to tidal forces, much greater than in the case just assumed, and of variable magnitude, owing to orbital eccentricity; yet no signs of an outburst have been observed in any of them. Some of these stars are dwarfs of the solar type of spectrum, and closely resemble the Sun in size and mass. There is, therefore, positive evidence against this hypothesis.

The collision hypothesis fares the worst of all. The perihelion distance is of the order of the Sun's radius, that is, the initial value of p is about 0.01 on the scale of Table V. The matter composing the ribbon would have initial velocities intermediate between those of the Sun and the star, and intermediate values of angular momentum per ton. If the star and Sun were equal in mass, they would swing around their center of gravity with equal and opposite velocities. The middle of the ribbon (composed of equal parts of solar and stellar material) would be left motionless at this point—equally attracted by the Sun and star—and would probably dissipate almost entirely into space, owing to its small mass and high temperature, as Bickerton long ago maintained. The part nearer the Sun, which alone could form planets, would be composed mainly of solar material, and would have an angular momentum per unit mass (relative to the Sun) less than half that of the star, that is, less than 0.07 on the scale of Table V. The difficulty of getting this out to the distance of the major planets is greater than ever.

All the forms of the encounter theory labor therefore under grave difficulties. How a star swinging around

the Sun at a distance of a million miles or so, and completing a half-circuit in a few hours, could cause great eruptions, is easy to understand. But how it could carry the greater part of the ejected material with it to a distance many hundred times as great, and then let it go, moving rapidly crosswise, while the star itself was by that time moving almost straight away from the Sun, is indeed a hopeless puzzle.

There seems to be no escape, if it is assumed that the star actually passed close to the Sun. If we suppose that it did not, two possible, but doubtful, alternatives present themselves.

The first is that, at the time of the encounter, the Sun, though not much larger than now, was in the state which precedes the outburst of a temporary star, or nova. During such outbursts, the surface layers of the star are uplifted bodily, and flung off into space, so powerfully that, after escaping from the star's attraction, they form a shell, and later a nebula, expanding radially at the rate of 1000 km/sec or even more. What the forces are which produce the cataclysm, and where the enormous amounts of energy which are requisite come from, no one yet knows. It is imaginable—though obviously very improbable—that while the Sun was in an unstable state, just ready for the explosion, the tidal influence of the passing star sufficed to set it off. A part—probably a small part—of the ejecta passed near enough to the star to be diverted into elliptical orbits. The most obvious difficulty about this suggestion is that the ejected masses would presumably have come off in all directions, and

should have passed on all sides of the star, above and below, as well as in front of it and behind it, so that the resulting orbits might as well have had large as small inclinations, and some of them should have been retrograde. The hypothetical eruption, too, must have been much less violent than that of an ordinary nova —otherwise the ejected matter would have gone by "so fearfully quick" that the star could not have held it back. Finally, there is no reason to suppose that large lumps would be ejected during such an explosion, or form afterwards. All in all, this notion need not be taken very seriously.

Another possibility, however, deserves more consideration. The present small diameter of the Sun is generally believed to represent a stable state, in which the loss of heat from the surface is balanced by the liberation of energy in the interior from some sub-atomic but still obscure source. Part of the Sun's lost energy may however have been derived from its contraction. To expand it to many times its present diameter, would demand the separation of all its parts against their mutual gravitation, and require a great expenditure of energy. Contraction from a large initial diameter would liberate a corresponding amount. Much of this (certainly more than half) would be used up in heating the gaseous interior of the body, and enabling it to withstand the increased gravitational pressure; but a surplus would be available for radiation. Contraction from a very large diameter, say that of Neptune's orbit, would thus free enough energy to keep the present rate of radiation going for about fifteen million

years. Geological evidence shows that the Earth's temperature has been much the same as now throughout the last billion or more of years. The Sun has therefore been shining at about its present rate for all that time, and *must* have had some other source of energy to draw upon.

There is good reason to believe that sub-atomic sources of energy would not be tapped except at an exceedingly high temperature. If the Sun had, at some remote epoch, been of large diameter and low density, it would even then have been gaseous, but its internal temperature would have been low, and the sub-atomic process would not have been operative. Eddington's analysis shows that its rate of radiation would have been much the same as at present. To maintain it, the primitive Sun would have to contract (as Lord Kelvin showed long ago). After ten or fifteen millions of years, as it approached its present size, we may suppose that the internal temperature became high enough to "turn on" the sub-atomic source. This would provide a new income of energy, and take over more and more of the substantially fixed expenditure. Contraction would slow up and cease, and the old, reliable, middle-aged luminary of our acquaintance would thus come into being.

We have no proof that this ever happened;—the Sun may always have been small since the remotest time about which we may safely draw conclusions. But it *may* perfectly well have happened; and, if a vagrant star passed by while the Sun was still of large diameter, the disparity between the initial and the final

distances of the ejected matter would not be so great.

It would still be serious enough, for we can hardly suppose the primitive Sun to have been larger than Mercury's present orbit, and there is still a hundred-fold increase in distance required to form Neptune and Pluto. The difficulties involved in the condensation of the ejected material into a few isolated bodies are no whit diminished; for, though cooler on the new hypothesis, it was also far less dense.

Moreover, there is little time for things to happen. On the Kelvin contraction hypothesis and at the present rate of radiation, the Sun could have been larger than Mercury's orbit only for 200,000 years, and in the next million would have shrunk to only a dozen times its present size—too small to help much.

Now the stars are so widely strewn in space that the probability of a close approach between any two of them is very small. In a region where stars like the Sun are scattered at the same average distance as the nearer stars—about six light years apart—Jeans calculates that a given star should actually collide with another once in 6×10^{17} years, or, to put the matter more intelligibly, that, if a billion stars were left to move at random for a billion years, there would be, on the average, about two collisions,—also some 400 approaches within the Earth's present distance from the Sun, and 4000 within Jupiter's. Disruptive encounters should therefore be excessively rare. The chance that a star, taken at random, should have undergone such a vicissitude during the past two billion

years is something like one in a million, on the most liberal assumptions, and less than one in a hundred million if a near-collision is really necessary to produce planets.

It would be altogether wrong to conclude from this that there is a million-to-one chance that our system was not produced by an encounter, for the Sun is not at all a star chosen at random. The existence of a system of planets is a necessary condition—as Eddington puts it—for "the evolution within it of beings capable of speculating upon its origin." If it could be proved that a planetary system could be produced by an encounter, and in no other way, we could be certain that our system, since it exists, had been so produced, even if the chances were heavily against it; and we would also be justified in concluding that there were few others in the Galaxy.

There are therefore very grave, if not fatal, difficulties about the existing theories which attempt to explain the origin of our system from a single mass by gravitational and dynamical processes, whether these arise from its own rotation or from an encounter with a passing body.

It has recently been suggested by Ross Gunn that ions might be ejected from the Sun by the combined action of its rotation and of crossed electric and magnetic fields, and by Alter that the pressure exerted by the radiation of a rotating Sun on a small particle moving around it would drive it to greater distances. Both suggestions have their difficulties; but it is needless to discuss them in detail here, for the proposed forces

could at most remove very small particles,—the tiniest planetesimals,—and the difficulties of gathering these together into large bodies have already been discussed. These theories might account for the zodiacal light, but not for the planets.

If the planets were not formed out of the Sun, they must have had an independent origin. Various hypotheses of this sort have been suggested. The oldest, which originated with Kant (1755), supposes that the Sun and planets originated together, out of a cloud of meteorites. If the bodies in such a swarm were moving nearly, but not quite, at random, and there was a high central condensation of slower-moving particles, the conditions of angular momentum might be satisfied. But collisions would soon smash the meteorites into the finest dust, if not into separate molecules, and form a thin cloud, substantially uniform except for an increase of density toward the center and a slow rotation. The segregation of large masses out of this presents the difficulties which have already been discussed, and we are forced to postulate the initial existence of massive nuclei or condensations—that is, of the planets themselves, only smaller! The usual difficulties about rotation and satellites still persist, so that this suggestion gets us no further.

The hypothesis that the system originated from an irregular and heterogeneous nebula, opens up wide possibilities—indeed, too wide. We have no longer a definite configuration to start with, nor one imposed more or less specifically by a dynamical process. By an appropriate choice of the initial configuration and

motions, we could probably come out with almost any assigned final arrangement; but if we adjust our premises to bring out the planetary system as a conclusion, we are in great danger of *ad hoc* assumptions.

For example, if the original material was distributed nearly in one plane, with motions almost in this plane, the resulting system would be flat, like our own; if it was not, the planetary orbits would be highly inclined to one another. But to *assume* that the initial distribution was flat, without giving reasons for this, is to beg the question—unlike the dynamical theories, which find a plane naturally determined by the rotation of the Laplacian nebula, or by the orbit of the star during the encounter.

We might—as Nölke suggests—try to work backward from the existing system, deducing its properties at ever remoter times. But so long as the separate bodies retain their identity and their present masses, we have still essentially the same system; if we assume them to have been formed by condensation, coalescence or capture, the problem of working backward has no unique solution.

Nölke has suggested (1930) that the Sun and planets were formed at substantially the same time from an arm or wisp of nebulosity which contained one large condensation—the primitive Sun—and a large number of smaller knots. Wisps or filaments can be observed in certain nebulæ; but we do not know of what they are composed (save for the luminous gas, which may be but a small part of the whole); whether a filament lies in one plane or is twisted; nor whether

the motions of its parts are parallel to any one plane or not. It would presumably be possible to devise an arrangement of these knots and their motions which would ultimately result in something closely resembling the solar system, even without making Nölke's assumption that radiation pressure at first counteracted almost the whole of the gravitational attraction, and then dropped to a small fraction of its former value during a few orbital revolutions of the primitive planets; but, in any case, the initial assumptions would be mainly *ad hoc*—as those by which he explains the rotations of the planets frankly are.

To explain the satellites—which offer one of the worst difficulties on all theories—Nölke adopts a modification of the old Laplacian scheme, and concludes that they were born within the "atmosphere" of the planet when the primitive mass, though already greatly concentrated toward the center, was still very widely extended. Since the angular momentum of the satellites is much less than that of the planet's rotation, this hypothesis escapes the objection which was so fatal in the case of the solar system. But the density of the outer portions of the assumed mass must have been exceedingly low, and the dynamical arguments which show that local condensations could not have formed in a region where the density was less than two per cent of the mean density of the whole mass retain their force.

If, however, one is prepared to postulate the preexistence of the nuclei of all the planets, and many, if not all, of the asteroids, why should one strain at a

gnat and object to a few more nuclei for the satellites? The extended planetary envelope acting as a resisting medium might then do valuable service in reducing the orbits to co-planar circles.

The distant satellites of Jupiter and Saturn, and the retrograde satellite of Neptune, are attributed by Nölke to true captures of independent bodies plunging into the resisting medium, aforesaid. The high orbital inclination of Neptune's satellite—which, by the amount of light which it reflects, may be nearly as big as Pluto—is perhaps in favor of this. But, if Neptune once had such a surrounding cloud, it must have been held up by the centrifugal force of the particles' motion, and not by gas pressure. If this was so, why is it not there still?

The hypothesis of origin in a nebula cannot therefore be summarily dismissed; but it demands so many special assumptions that, as Moulton well said of a suggestion regarding the origin of double stars, "we do not explain anything, we only push by an assumption the problem of explaining . . . a little farther into the unknown."

Comets' motions are so unlike those of planets that it is hard to account for their origin by the same hypothesis. Not only are their orbits inclined nearly at random, but the directions of their aphelia are distributed almost indiscriminately over the celestial sphere.

Perturbations by the planets could hardly account for this,—indeed, as Fessenkoff has shown, captured comets are far more likely to be left moving nearly in

the plane of the planets than at right angles to it. Perturbations by the stars, however, might alter the inclinations greatly, and produce a nearly random distribution, as Öpik has shown. But even these should not seriously alter the direction of the aphelion of an orbit.

On the tidal or collision hypotheses, splashes of matter may easily have been flung off with nearly the parabolic velocity in various directions, but all nearly in the plane of the star's orbit. Their aphelia should continue to show a strong concentration toward this plane. Chamberlin meets this difficulty by the assumption that comets are formed from small particles—"chondrulites,"—expelled from the Sun,—in all directions, but not at the time of the planetesimal encounter—and collected into swarms far out in interstellar space, in some fashion or other; but forces otherwise unknown would be required to produce either of these effects.

A further difficulty, and a very serious one, in attributing the comets to the same source as the planets, is the irrevocable loss of substance at each perihelion passage, discussed in Chapter II. This has led both Bobrovnikoff and Nölke to the conclusion that the comets are relatively recent acquisitions added to the system while it by chance traversed a nebula, not many millions of years ago. There is extensive nebulosity in the region of the heavens away from which the Sun is moving, especially in the region of Orion, and at a probable distance of a few hundred light years, so that the Sun may perfectly well have passed through a part

of this ten million years ago—more or less. If the hypothetical nebula was itself moving in space relative to the average of the stars, we should look for it now in some other direction (almost anywhere) and it may be nearer.

As the Sun passed through such a nebula, its particles would swing around in hyperbolic orbits, and there would be a decided temporary concentration in the axial line, straight behind the Sun, where particles were coming in from all directions. Some of these would collide and form a cloud of gas or dust, almost stationary with respect to the Sun, so long as the passage through the cloud continued. Swarms of particles, passing through this cloud, would suffer resistance, which might perhaps be great enough to change their orbits from hyperbolas to ellipses, and thus a flock of comets would be attached to our system.

These comets, however, would recede from the Sun almost in the direction in which they had come, so that their aphelia should be strongly concentrated in the direction from which the nebula had approached, and opposite to that in which it now lies. No such conspicuous concentration in any direction exists. Moreover, the present number of comets is so great—more than a hundred thousand—that this parent nebula must have been extraordinarily rich in condensations, for only those whose paths had led them close to the Sun could have been retarded enough to be captured. All told, then, the comets remain one of the greatest enigmas of all.

Among all this uncertainty one bit of history, and

only one, stands out clearly. We *can* reckon back, in the case of our own Moon, till we come to a situation very different from the present.

It has already been told how the friction of the tides is gradually slowing the Earth's rotation, and as an inevitable consequence, pushing the Moon about five feet farther away every century. In the past the day must have been shorter and the Moon nearer. As we go back, we find the day and the month both shorter, the tides higher, and the changes more rapid, until we reach a situation in which the day and the month are nearly equal, and the tides move over the Earth more slowly. At the limit we find the Earth rotating in a little less than five hours; the Moon's center but 9000 miles from the Earth's, and the month but a very little longer than the day; the Moon's orbit-plane nearly coincident with the Earth's equator, and both inclined 12° to the plane of the Earth's orbit.

These results were established by the detailed and careful work of Sir George Darwin. The numerical values were derived without allowance for the friction of the solar tides—which is continually robbing the Earth of angular momentum, and transferring it to the planet's orbital motion. Exact allowance for this is difficult; but Darwin concludes that the initial period was about four hours, and the distance some 8000 miles. This would leave a gap between the Earth and Moon of little more than a third of the Earth's diameter, and it is natural to inquire whether, if we could go still farther back, we would not find them united into a single mass.

This, however, is more than doubtful. Moulton has calculated that a single body, with the mass and volume of the Earth and Moon combined, and the given angular momentum, would be a stable spheroid —flattened more than Saturn, but not twice as much, and in no danger of breaking up, owing to its rotation. Darwin had earlier suggested that the disruption might nevertheless have been caused by the solar tides. Ordinarily, these would be only a few feet high; but if the period of the tides, imposed from without, should happen to coincide exactly with a natural free period of vibration of the mass, the oscillations might build up steadily to very great magnitude and ultimately lead to the separation of a portion. It would of course be excessively improbable that the two periods were, by chance, exactly the same; but in a cooling fluid mass they would both gradually change, but at different rates, and so might be brought into coincidence.

Jeffreys at first considered that, for a planet with a dense core and a thick envelope of molten rock, this might well happen. But in a later paper (1930), he showed that the solar tides would cause currents in the lava shell, relative to the metallic nucleus (which would be much less affected by them) and that the friction of these currents would prevent the tides from attaining a height of more than 150 or 200 miles—impressive enough in itself, but very far short of the amount required to detach any part of the top of the wave. His conclusion, "that the Moon has been separate from the Earth ever since the early catastrophe that formed the planets," has been reached independ-

ently, by different lines of argument, by several other investigators.

Why a mass of matter, escaping from this terrific turbulence, should emerge as two bodies, so unequal in size and so close together as the Earth and Moon must then have been, is by no means easy to understand. But no exact calculations can be made in so complicated a situation, and no one can therefore claim it to be impossible.

One further effect of tidal friction in the system has long been recognized. The Moon keeps always the same face toward the Earth—the tides have done their utmost, and are now, so to speak, "frozen" in the form of a small permanent elongation of the Moon toward the Earth, amounting to about one part in 1500. This is much greater than the present tidal forces would produce in a fluid Moon, but agrees very well with the effect to be expected if the Moon was 90,000 miles from the Earth.

It looks then as if the Moon had frozen to the core —in the sense of becoming completely rigid—when she was at only three-eighths her present distance from the Earth, and so retained "a fossil tide that has persisted through geological time." Jeffreys—the author of this effective phrase—has shown that the capacity to resist long-continued strain which this demands in the material of the Moon is no greater than that which appears to exist in the interior of the Earth. This fossil tide would obviously exert no friction; hence the question arises why the Moon does not keep on rotating with the period she must have had when she "froze

up"—about six days. Jeffreys answers this very prettily. If the Moon's rotation had remained unchanged while her orbital period became longer, owing to tides on the Earth, her longest axis would no longer point exactly toward the Earth. As soon as this happened the attraction of the Earth on this protuberance (slightly exceeding that on the corresponding one at the back) would exert a small, but continuous force—what engineers call a torque—tending to turn the Moon back so that she faced the Earth exactly once more—in the present case, to slow her rotation. This force is very small, but so is the effect to be produced. Jeffreys calculates that, if the long axis of the Moon, on the average, points ahead of the Earth's center by 1/5000 of a second of arc, the resulting change in her rotation would balance the present change in the length of the month. This is an amazingly small amount—it is equivalent to shifting the middle of the Moon's disk by only 1/15 of an inch! It is doubtful whether any other effect so conspicuous is produced by a cause so minute.

The four great satellites of Jupiter, and two or three of Saturn's, show regular variations in brightness which indicate that each one rotates in its orbital period. Tidal action doubtless accounts for this, and probably also for the fact that Mercury keeps the same face toward the Sun.

If the tides raised by the satellites on their primaries produced as much friction, in proportion to their height and speed, as those on the Earth, very great changes would occur. For several satellites—

notably Jupiter's first satellite, Neptune's satellite, and Phobos, the inner satellite of Mars—the distances should change with thousands of times as rapid a time-scale as for the Moon. We can be quite sure that this has not happened, especially for the last two bodies. Phobos revolves in its orbit faster than Mars rotates, while Neptune's satellite goes backward. In both these cases the effect of tidal friction is to bring the satellite nearer the planet,—so that ultimately it will fall into it or else break into many pieces and form a ring. Since the satellites are still there, the tidal friction must be small. Mars is however a solid body, with very little liquid water, if any, on its surface. The tides raised by Phobos must cause a slight elastic distortion of the solid body of the planet, but there is good reason to believe that this is accompanied by very little friction.

Neptune, on the contrary, is almost certainly gaseous on the surface, and tides in a gaseous atmosphere would offer practically no friction at all—nor would those in an ocean below it, if this were deep, and covered the whole planet, with no coasts or shoals to obstruct the tide. It is probable, then, that the course of tidal evolution in the Earth-Moon system is a local peculiarity, depending literally on geography, and unlikely to be duplicated elsewhere. Even in this favorable case, our reasoning carries us back to a state which is not essentially different from the present, and gives us no clue regarding the origin of the bodies with which we are dealing.

Past studies of the origin of our system appear, then,

to have ended in an impasse. We are like a group of engineers trying to find a route from the mouth of a canyon to the plateau above. Explorations up the stream, no matter what branch they follow, lead only into box canyons, up which they can go no further. Landing on the plateau, by some flight of the imagination, they find "draws" which lead downward—but when followed turn aside and evidently tend to quite different outlets. But here our allegory breaks down. The canyon may well be impassable, affording no through route. But the solar system must have had an origin of some kind. If we have not discovered it, we must have failed to follow up all the possibilities, or have turned back somewhere on a mistaken belief that there was no way through. It behooves us, therefore, to explore every possible ramification before we give up.

The most encouraging direction for this attempt would still appear to be in the modification of the hypothesis of an encounter. The composition of the Earth's atmosphere suggests strongly that our planet, at the beginning of its independent existence, was very hot for a short time (as has been told in detail in Chapter II), and all that we know of the atmospheres of the other planets fits in well with this view. Moreover, the rarity of lithium and beryllium indicates that, at some time or other, the matter which now composes the Earth had a temperature of the order which prevails in the interior of the stars. These facts are simply explicable on any theory which attributes the origin of the planets to matter separated from

the Sun,—by whatever process. But there is little or no reason why we should find such peculiarities of composition in masses which had segregated independently from a nebula which has "always" been cool.

The difficulty about angular momentum still seems fatal to the Laplacian hypothesis: is there no way out by an encounter?

Two possibilities, at least, appear, which do not seem to have been previously suggested.

The first is that before the encounter, the Sun was a binary star, having a companion a good deal smaller than itself, revolving about it at a distance comparable with those of the major planets, and that a collision between this body and a passing star (or perhaps even a close approach) broke this companion into fragments, which developed into the present planets. The initial postulate is not seriously improbable, for one-tenth, or more, of all the stars are binaries, and many have been observed to have faint companions (doubtless therefore of small mass) despite the observational difficulty of seeing faint stars so close to bright ones. A collision is as improbable as ever, but not much more so.

On this assumption, much of the planets' angular momentum may have been primitive—the collision serving rather to distribute it differently among the planets than to impart it *de novo*. The rotations of the major planets could be accounted for by collision—and it is worth recalling that they are conspicuously *not* about parallel axes. The satellites remain trouble-some—and the terrestrial planets become hard to

account for. Three more serious difficulties are these. First, it is necessary either to assume that the Sun's companion was of small mass (less than one per cent of its primary) or to get rid of the rest.

I see no way of doing the latter, except on the wild assumption that the passing star made an almost central collision, and carried everything away with it except a few splashes. The trouble about assuming a small body—say of 1/100 the Sun's mass—to begin with is that we have no evidence whether such bodies exist at all among the stars, and, if so, how many there are. They would shine too feebly to be seen by their own light, be so small that, even if they eclipsed their primaries, the loss of light would be detected only by very precise observations, and their masses would not suffice to produce perceptible gravitational influences. Down to the limit of faintness to which we can observe—about 1/10,000 of the Sun's light, and probably about a tenth of its mass—the fainter bodies are more numerous, in equal volumes of space, than the brighter. So this is not much of a difficulty.

Second, we do not know whether a collision would be capable of breaking up a single mass into several of comparable size,—and a mathematical treatment of this problem would be exceedingly difficult.

Third, it is unlikely that the plane of the orbit of the original companion about the Sun and that of the intruding star would be even roughly parallel. If not, the dissevered fragments would be left moving in orbits highly inclined to one another. The supposable evolution of the initial orbits into more nearly circu-

lar forms has also all the difficulties previously mentioned.

This then is not a promising hypothesis. Another may, however, deserve more consideration.

One of the most striking results of modern investigation has been the way in which several different and quite independent lines of evidence indicate that a very great event occurred about two thousand million years ago. The radio-active evidence for the age of the Earth; the similar evidence for the age of meteorites; and the estimated time for the tidal evolution of the Moon's orbit (though this is much rougher), all agree in their testimony, and, what is far more important, the red-shift in the nebulæ indicates that this date is fundamental, not merely in the history of our system, but in that of the material universe as a whole.

The history of our planet is thus tied up with that of the whole relativistic "world." It is generally recognized that one of the possible types of solutions of the general equations which define this—and a type consistent with present observed data—leads to the conclusion that, at an epoch a billion or two years ago, the material bodies which are now accessible to observation were crowded together in a much smaller volume of space than they now occupy. This conclusion follows from those particular solutions according to which space itself was far less extensive then than now, but may also be deduced from solutions in which space is infinite at all times. Other solutions are possible; but the majority of the principal investigators are sympathetic toward the type just described.

At or near this epoch, all sorts of things may have happened. We do not know whether even the stars themselves are older. It may be that, as de Sitter has suggested, they were pre-existent; and that many of them came unscathed through the crisis. Even so this would have been the time *par excellence* for encounters of all sorts. Or it may be that a cosmic New Deal occurred, and that, just afterwards, matter was distributed more widely, but more thinly, through space, to settle down into the stars. If this is so, collisions between the huge aggregates, destined to grow into stars, may have been numerous. Most of the difficulties of the collision hypothesis disappear, and planetary systems may be fairly numerous.

Or, again, it may be that at the start, all the matter of the Universe was tightly packed together, perhaps into the one great Atom, which forms the starting point of Lemaître's hypothesis,—which deserves no less respect because of its picturesqueness. With this as a start, almost anything may have happened during the furious years and centuries in which the present Universe began to take shape, and we need no longer worry about details. The choice between these alternatives is not now possible; indeed, there may be still others. But the evidence that the age of our Earth, and of the meteorites which belong to our system, is substantially the same as that of the meteorites which come from outside it, and of the far-flung assemblage of nebulæ, can hardly be gainsaid—nor is its importance likely to be underestimated.

We conclude, then, at last, that no one can yet say

how our system originated in detail, but that we may reasonably regard its birth as the merest incident in a far vaster process,—the shaping of the material Universe as we know it. What lay behind that shaping we do not know. Our searching has brought us no nearer the Power whence all things proceed than did Job's colloquy with his friends. But one who has attempted to set out in order what little we have learned or may surmise may hope, at least, that his endeavors may seem less destructive and even perhaps more profitable than those of Browning's poet and philosopher, who had

> "Written three books on the Soul
> Proving absurd all written hitherto
> And putting us to ignorance again." [1]

[1] Cleon.

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